Environmental and Natural Resource Economics

A Contemporary Approach

Fourth Edition

Jonathan M. Harris and Brian Roach

Environmental and Natural Resource Economics

Environmental issues are of fundamental importance, and a broad approach to understanding the relationship of the human economy and the natural world is essential. In a rapidly changing policy and scientific context, this new edition of *Environmental and Natural Resource Economics* reflects an updated perspective on modern environmental topics.

Now in its fourth edition, this book includes new material on climate change, the cost-competitiveness of renewable energy, global environmental trends, and sustainable economies. The text provides a balanced treatment of both standard environmental economics and ecological economics, based on the belief that these two approaches are complementary. Several chapters focus on the core concepts of environmental economics, including the theory of externalities, the management of public goods, the allocation of resources across time, environmental valuation, and cost-benefit analysis. Material on ecological economics includes such topics as macroeconomic scale, entropy, and "green" national accounting. Topical chapters focus on: energy; climate change; water resources; international trade; forests; fisheries; and agriculture, with an emphasis on designing effective policies to promote sustainability and a "green" economy.

Harris and Roach's premise is that a pluralistic approach is essential to understand the complex nexus between the economy and the environment. This perspective, combined with its emphasis on real-world policies, is particularly appealing to both instructors and students. This is the ideal text for classes on environmental, natural resource, and ecological economics.

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Preface to the Fourth Edition

The fourth edition of *Environmental and Natural Resource Economics*: *A Contemporary Approach* maintains its essential focus on making environmental issues accessible to a broad range of students. The text is a product of over 20 years of teaching environmental and natural resource economics at the undergraduate and graduate levels. It reflects the conviction that environmental issues are of fundamental importance, and that a broad approach to understanding the relationship between the human economy and the natural world is essential.

Environmental economics, and environmental issues in general, are of great current importance and subject to rapid change. In preparing the fourth edition, we have developed much new material and updated perspectives on key issues. Perhaps the most dramatic changes are in the areas of energy and climate change. Chapters have been reorganized to create a new section on "Energy, Climate Change, and Greening the Economy," in which we present the rapid spread of renewable energy, the increased urgency of climate change and new policies to respond to it, and address the broader questions involved in developing an economy compatible with environmental sustainability.

The text retains its balanced approach to environmental and ecological economics. In our view, these two approaches are complementary. Many elements of standard microeconomic analysis are essential for analyzing resource and environmental issues. At the same time, it is important to recognize the limitations of a strictly market-based or cost-benefit approach, and to introduce ecological and biophysical perspectives on the interactions of human and natural systems. This perspective makes it possible to achieve a broad focus on inherently "macro" environmental issues, such as global climate change, ocean pollution, population growth, and global carbon, nitrogen, and water cycles.

NEW TO THE FOURTH EDITION

The fourth edition of *Environmental and Natural Resource Economics*: *A Contemporary Approach* has been updated in response both to developments in the world of environmental policy and to comments and suggestions based on classroom use. New and revised material in the fourth edition (note new chapter numbering) includes:

- Chapter 1: Reorganization of the material on environmental and ecological economics to provide clearer distinctions between the two approaches.
- Chapter 2: A new section on recent environmental trends has been added.
- Chapters 6 and 7: The third edition chapter on valuation and cost-benefit analysis has been divided into a chapter specifically on valuation and another on cost-benefit analysis, including more practical examples and in-depth discussion both of methodologies and limitations of valuation and cost-benefit techniques.

- Chapter 8: This chapter on pollution analysis and policy has been moved to earlier in the text, in order to bring all the core concepts of environmental economics into the same section.
- Chapter 11: Discussion of changing energy production and consumption patterns, the increasing cost-competitiveness of renewable energy, and the potential for expansion of renewables and increased efficiency.
- Chapters 12 and 13: A review of new scientific evidence on climate change and global climate change policy, including the most recent Intergovernmental Panel on Climate Change reports and the 2015 Paris climate agreement. A new focus is the potential for carbon storage in forests and soils. Other features include discussion of the possibility of catastrophic impacts and the policies needed to avoid them, the European Union Emissions Trading Scheme and other carbon trading systems, and carbon taxes in Canada and elsewhere.
- Chapter 14: The chapter on the Green Economy has been extensively updated to include the most recent empirical analyses of the relationship between the economy and the environment.
- Chapter 15: New material on recent population developments, including changing fertility rates, projections for population growth through 2050 and beyond, and practical examples of population policies.
- Chapter 16: Updated projections for agricultural demand and supply, the impact of the "food crisis," rising meat consumption, biofuels, climate change, and genetically modified crops.
- Chapter 20: An expanded chapter on water economics, including analysis of virtual water and water footprint, water demand management, water pricing, and water privatization.
- Chapter 22: A new section on the UN's global Sustainable Development Goals, policies needed to achieve them, and data on potential job creation through renewable energy development.

Throughout all chapters we have updated data and figures, drawing on the most recent data on population growth, energy use, carbon emissions, mineral prices, food production and prices, and renewable resource supply and demand. Two-color printing makes the figures more user-friendly. Many new boxes have been added and others updated to provide current real-world context for the issues discussed in the text.

ORGANIZATION OF THE TEXT

The text is structured so as to be appropriate for a variety of courses. It assumes a background in basic microeconomics and can be used in an upper-level undergraduate course or a policy-oriented master's-level course. Part I provides a broad overview of different approaches to economic analysis of resources and environment and of the fundamental issues of economy/environment interactions. Part II covers the basics of standard environmental and resource economics, including the theory of externalities, resource allocation over time, common property resources, public goods, valuation, cost-benefit analysis, and pollution control policies. Part III offers an introduction to the ecological economics approach, including fundamental concepts of ecological economics, payment for ecosystem services, and "greening" national accounts.

Part IV covers energy, climate change, and policies for a green economy. These chapters have been placed together for a more cohesive approach to some of the central issues of developing sustainable economic systems. Part V focuses on population, agriculture, and resources, including reviewing different theories of population and its relationship to the economy and the environment, giving an overview of the environmental impacts of world agricultural systems and discussing issues of renewable and nonrenewable resource supply, demand, and management.

Part VI brings together the themes developed in the preceding chapters in a consideration of environmental impacts of trade and policies for sustainable development.

PEDAGOGICAL AIDS FOR STUDENTS AND INSTRUCTORS

Each chapter has discussion questions, and the more quantitative chapters have numerical exercises. Key terms in each chapter are compiled in an extensive glossary. Useful web sites are also listed. Instructors and students are urged to make full use of the text's supporting web sites at **http://www.gdae.org/environ-econ.**

The instructor web site includes teaching tips and objectives, answers to text problems, and test questions. The student site includes chapter review questions and web-based exercises. The support sites will be updated periodically with bulletins on topical environmental issues.

ACKNOWLEDGMENTS

The preparation of a text covering such an extensive area, in addition to the supporting materials, is a vast enterprise, and our indebtedness to all those who have contributed to the effort is accordingly great. Colleagues at the Global Development and Environment Institute have supplied essential help and inspiration. Research Associate Anne-Marie Codur has made extensive contributions to this edition, especially in the chapters on climate change, population, agriculture, water, and sustainable development. This edition, like previous editions, would not have been possible without the unwavering support of the Institute's co-director, Neva Goodwin, who has long championed the importance of educational materials that bring broader perspectives to the teaching of economics.

Our colleagues Timothy Wise, William Moomaw, Frank Ackerman, Kevin Gallagher, and Julie Nelson have provided insights on specific issues. Research support and technical expertise, especially in presenting data and graphics, was organized by Mitchell Stallman, ably assisted by Max Schmulewitz and Jacob Mittelman. Angela Trowbridge and Erin Coutts provided administrative and outreach support.

This and previous editions have greatly benefited from the comments of reviewers and users including Kris Feder, Richard Horan, Gary Lynne, Helen Mercer, Gerda Kits, Gina Shamshak, Jinhua Zhao, John Sorrentino, Richard England, Maximilian Auffhammer, Guillermo Donoso, Mitchell Dudley, Lawrence McKenna, and Alfonso Sanchez-Penalver. Faculty members, including Fred Curtis, Rafael Reuveny, Ernest Diedrich, Lisi Krall, Richard Culas, and many others in the United States and worldwide, have provided valuable feedback from class use. Others whose work has provided special inspiration for this text include Herman Daly, Richard Norgaard, Richard Howarth, Robert Costanza, Faye Duchin, Glenn-Marie Lange, John Proops, Joan Martinez-Alier, and many other members of the International Society for Ecological Economics. Our editors at Routledge, Andy Humphries, Laura Johnson, and Sarah Douglas, have provided support and guidance throughout. Finally we thank the many students we have had the privilege to teach over the years—you continually inspire us and provide hope for a better future.

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PART

I

Introduction: The Economy and the Environment

CHAPTER

1

Changing Perspectives on the Environment

Chapter 1 Focus Questions

- What major environmental issues do we face in the twenty-first century?
- What are the main frameworks that economists use to understand these issues?
- What principles can promote economic and ecological sustainability?

1.1 OVERVIEW OF ENVIRONMENTAL ISSUES

Over the past five decades, we have become increasingly aware of environmental problems at the local, national, and global levels. During this period, many natural resource and environmental issues have grown in scope and urgency. In 1970, the Environmental Protection Agency was created in the United States to respond to what was at that time a relatively new public concern with air and water pollution. In 1972, the first international conference on the environment, the United Nations Conference on the Human Environment, met in Stockholm. Since then, growing worldwide attention has been devoted to environmental issues. (See Box 1.1 for more important events in modern environmental history.)

In 1992 the United Nations Conference on Environment and Development (UNCED) met in Rio de Janeiro, Brazil, to focus on major global issues, including depletion of the earth's protective ozone layer, destruction of tropical and old-growth forests and wetlands, species extinction, and the steady buildup of carbon dioxide and other "greenhouse" gases causing global warming and climate change. Twenty years later, at the United Nations Rio + 20 Conference on Sustainable Development, countries of the world reaffirmed their commitment to integrating environment and development but acknowledged limited progress toward these goals.[1] In 2012, the United Nations Environment Programme (UNEP) report *Global Environmental Outlook 5* found that "burgeoning populations and growing economies are pushing ecosystems to destabilizing limits." According to the report:

> [The twentieth century] was characterized by exceptional growth both in the human population and in the size of the global economy, with the population quadrupling to 7 billion [in 2011] and global economic output increasing about 20-fold. This expansion has been accompanied by fundamental changes in the scale, intensity, and character of society's relationship with the natural world. . . . Drivers of environmental change are growing, evolving, and combining at such an accelerating pace, at such a large scale and with such widespread reach, that they are exerting unprecedented pressure on the environment.[2]

With the exception of ozone depletion, an area in which major reductions in emissions have been achieved by international agreement, the UNEP report offers evidence that the global environmental problems identified at UNCED in 1992 in the areas of atmosphere, land, water, biodiversity, chemicals, and wastes have continued or worsened. Other UNEP *Global Environmental Outlook* reports have identified nitrogen pollution in freshwater and oceans, exposure to toxic chemicals and hazardous wastes, forest and freshwater ecosystem damage, water contamination and declining groundwater supplies, urban air pollution and wastes, and overexploitation of major ocean fisheries as major global issues.

Climate change has emerged as perhaps the greatest environmental threat of our time. The 2014 report by the United Nations' Intergovernmental Panel on Climate Change concludes that:

> continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems.[3]

In December 2015, a United Nations conference held in Paris resulted in a 195-country agreement to limit and eventually reduce the greenhouse gas emissions that cause climate change.

Box 1.1 IMPORTANT EVENTS IN MODERN ENVIRONMENTAL HISTORY

1962: The publication of Rachel Carson's *Silent Spring*, widely recognized as the catalyst of the modern environmental movement, details the dangers posed by excessive pesticide use.

1964: The passage of the Wilderness Act in the United States, which protects public lands that are "untrammeled by man, where man himself is a visitor who does not remain."

1969: The Cuyahoga River in Ohio is so polluted by oil and other chemicals that it catches on fire, prompting widespread concern about water pollution and eventually the passage of the Clean Water Act in 1972.

1970: The creation of the Environmental Protection Agency by President Richard Nixon. Also, over 20 million participate in the first Earth Day on April 22.

1972: The creation of the United Nation's Environment Programme (UNEP), headquartered in Nairobi, Kenya.

1979: The partial meltdown of the Three Mile Island nuclear reactor in Pennsylvania raises concerns about the safety of nuclear energy. These concerns are exacerbated by the explosion of the Chernobyl reactor in the Soviet Union in 1986.

1987: The United Nations' Brundtland Commission publishes "Our Common Future," which defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

1992: The Rio Declaration on Environment and Development recognizes "the integral and independent nature of the Earth, our home," and lists 27 principles of sustainable development including reducing global inequities, international cooperation, and the promotion of an economic system that addresses environmental problems.

1997: The Kyoto Protocol is negotiated, the first international treaty that commits ratifying nations to reduce their greenhouse gas emissions. Although rejected by the United States, the treaty was ratified by 191 nations and entered into force in 2005.

2002: The Johannesburg Declaration on Sustainable Development recognized that "humanity is at a crossroads" and there exists "a collective responsibility to advance and strengthen the . . . pillars of sustainable development—economic development, social development, and environmental protection."

2009: Nations participating in climate change talks in Copenhagen agree that actions should be implemented to limit eventual global warming to no more than 2°C, though no binding commitments are made to reduce emissions.

2015: The Paris Agreement on climate change, approved by 195 countries, calls for a "global peaking of greenhouse gas emissions as soon as possible" with a goal of "holding the increase in global average temperature to well below 2°C above pre-industrial levels." Over 150 countries submit plans to limit their greenhouse gas emissions.

Also in 2015, the United Nations adopted the Sustainable Development Goals including combating climate change and environmental degradation.

Underlying all these problems is global population growth, which adds more than 70 million people a year. World population, which surpassed 7 billion in 2011, is expected to grow to around 9.7 billion by 2050, with almost all of the growth occurring in developing nations.[4]

Scientists, policy makers, and the general public have begun to grapple with questions such as: What will the future look like? Can we respond to these multiple threats adequately and in time to prevent irreversible damage to the planetary systems that support life? One of the most important components of the problem, which rarely receives sufficient attention, is an economic analysis of environmental issues.

Some may argue that environmental issues transcend economics and should be judged in different terms from the money values used in economic analysis. Indeed, this assertion holds some truth. We find, however, that environmental protection policies are often measured—and sometimes rejected—in terms of their economic costs. For example, it is extremely difficult to preserve open land that has high commercial development value. Either large sums must be raised to purchase the land, or strong political opposition to "locking up" land must be overcome. Environmental protection organizations face a continuing battle with ever-increasing economic development pressures.

Often public policy issues are framed in terms of a conflict between development and the environment. An example is the recent debate over "fracking," or hydraulic fracturing, to obtain natural gas. Producing natural gas can be profitable and increase energy supplies, but there are social and environmental costs to communities. Similarly, opponents of international agreements to reduce carbon dioxide emissions argue that the economic costs of such measures are too high. Supporters of increased oil production clash with advocates of protecting the Arctic National Wildlife Refuge in Alaska. In developing countries, the tension between the urgency of human needs and environmental protection can be even greater.

Does economic development necessarily result in a high environmental price? Although all economic development must affect the environment to some degree, is "environment-friendly" development possible? If we must make a tradeoff between development and the environment, how should the proper balance be reached? Questions such as these highlight the importance of environmental economics.

1.2 ECONOMIC APPROACHES TO THE ENVIRONMENT

While economists have thought about various natural resource issues for hundreds of years, the existence of **environmental economics**[5] as a specific field of economics dates back only to the 1960s, concurrent with the growing awareness of environmental issues discussed above.[6] Environmental economists apply mainstream economic principles to environmental and natural resource issues.

Even more recently (dating back to the 1980s), **ecological economics** has emerged as a field which brings together viewpoints from different academic disciplines to study the interactions between economic and ecological systems. Unlike environmental economics, ecological economics is defined not so much by the application of a particular set of economic principles, but by analyzing economic activity *in the context of* the biological and physical systems that support life, including all human activities.[7]

We will draw upon both approaches in this book. For most of the remainder of this chapter we will discuss the main differences between the two approaches. However, we should first emphasize that the boundary between environmental and ecological economics is a blurred one, with considerable overlap. A 2014 review of journal articles published in both fields finds that they have grown closer over time.[8] Some economists consider

environmental economics a field of economics which applies mainstream economic principles to environmental and natural resource issues

ecological economics a field which brings together viewpoints from different academic disciplines and views the economic system as a subset of the broader ecosystem and subject to biophysical laws.

the two fields to have essentially merged into "environmental and ecological economics."[9] Others call for a new term, such as "sustainability economics" which "lies at the intersection of the two and uses concepts and methods of both."[10]

The economic and ecological analyses that we will review offer a spectrum of viewpoints which can all contribute to solving myriad environmental challenges. But enough differences still exist so that one can differentiate between environmental economics and ecological economics in several respects. We now try to do that in more detail.

Main Principles of Environmental Economics

Environmental economics is based on the application of several mainstream economic theories and principles to environmental issues. We can identify the core of environmental economics as being comprised of four concepts:

1. The theory of environmental externalities
2. The optimal management of common property and public goods
3. The optimal management of natural resources over time
4. The economic valuation of environmental goods and services

Economists since the time of Adam Smith in the eighteenth century have asserted that voluntary market exchanges between buyers and sellers leave both parties better off than when they started. But market exchanges can also impact parties other than the buyers and sellers, either in a positive or negative manner. For example, someone buying gasoline affects other people, such as those exposed to air pollution from producing and burning the gasoline. Economists have long recognized that these "third-party" impacts, known as **externalities**, need to be considered when assessing the overall costs and benefits of market activity. Economic theory provides guidance on devising effective policies in the presence of externalities. We will explore externalities in more detail in Chapter 3.

> **externalities** an effect of a market transaction that impacts the utility, positively or negatively, of those outside the transaction.
>
> **market failure** situations in which an unregulated market fails to produce an outcome that is the most beneficial to society as a whole.
>
> **common property resource** a resource that is available to everyone (nonexcludable), but use of the resource may diminish the quantity or quality available to others (rival).
>
> **public goods** goods that are available to all (nonexcludable) and whose use by one person does not reduce their availability to others (nonrival).

Externalities are an example of **market failure**—situations in which an unregulated market fails to produce an outcome that is the most beneficial to society as a whole. Another important instance of market failure is the allocation of **common property resources** such as the atmosphere and the oceans, and **public goods** such as natural parks and wildlife preserves. Because these resources are not privately owned, we normally can't rely upon markets to maintain them in adequate supply, and in general the principles governing their use are different from those affecting privately owned and marketed goods. Environmental economists have developed a set of economic theories relevant to common property resources and public goods, which we will explore further in Chapter 4.

A third application of mainstream economic theory deals with the management of natural resources over time. According to this perspective, natural resources should be managed to provide society with the highest aggregate benefits summed across generations. A critical question in this analysis is how we value benefits that occur in the future relative to benefits received in the present. We present a basic model of resource management over time in Chapter 5.

The final core concept in environmental economics is that most environmental goods and services can, in principle, be valued in monetary terms. Environmental economists use a set of methods for estimating the monetary value of such things as asthma cases caused as a result of air pollution, the benefits of endangered species, or the value of a scenic view. By measuring these impacts in monetary terms, economists seek to determine the "optimal" degree of environmental protection based on a comparison of costs and benefits. We will discuss methods of valuation, and how they are applied, in Chapters 6 and 7.

Core Concepts of Ecological Economics

The core concepts in ecological economics are somewhat harder to define, as it is a broader field than environmental economics. There is also more variation in viewpoints and disciplinary approaches among ecological economists, including perspectives from biology, ecology, and other sciences, as well as engineering, systems modeling, history, and philosophy.

Nonetheless, we can identify a set of core concepts to which ecological economists generally subscribe. These three core concepts are:

1. The economic system is a subset of the broader ecological system
2. Sustainability should be defined according to ecological, rather than economic, criteria
3. It is essential to rely upon a range of academic disciplines and perspectives, in addition to economics, to provide insight into environmental issues

These core concepts have implications for both how economic analysis is conducted and for policy recommendations. We will explore each of these three core concepts in this chapter, comparing them to mainstream environmental economic approaches, and will return to their implications for analysis and policy in greater detail in Chapter 9.

1.3 PRINCIPLES OF ECOLOGICAL ECONOMICS

The Economic System in an Environmental Context

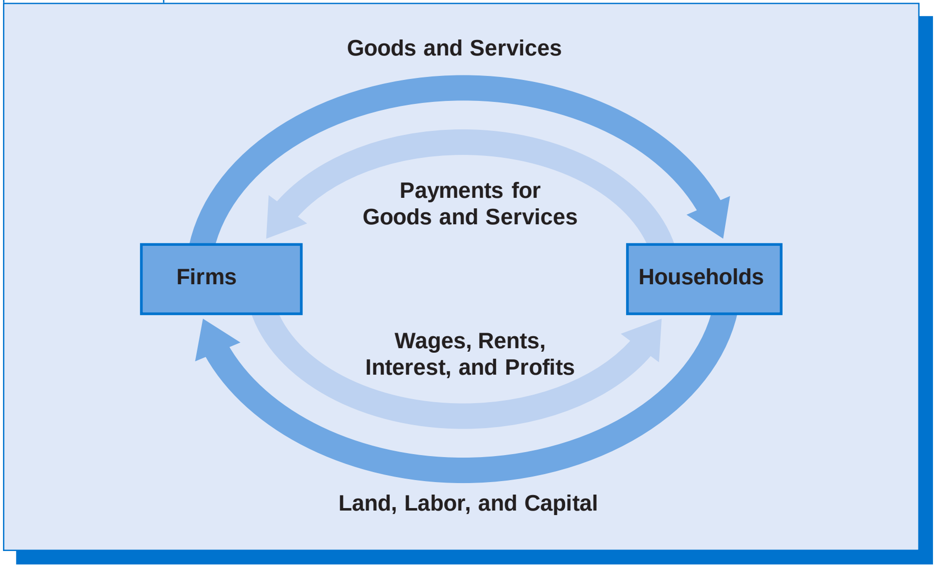
A basic building block of mainstream economic theory is the **standard circular flow model** of an economic system. As illustrated in Figure 1.1, this simple model depicts the relationships between households and business firms in two markets: the market for goods and services and the market for factors of production. Factors of production are generally defined as land, labor, and capital. The services that these factors provide are "inputs" into the production of goods and services, which in turn provide for households' consumption needs. Goods, services, and factors flow clockwise; their economic values are reflected in the flows of money used to pay for them, moving counterclockwise. In both markets, the interaction of supply and demand determines a market-clearing price and establishes an equilibrium level of output.

Where do natural resources and the environment fit in this diagram? **Natural resources**, including minerals, water, fossil fuels, forests, fisheries, and farmland, generally fall under the inclusive category of "land." The two other major factors of production, labor

standard circular flow model a diagram that illustrates the ways goods, services, capital, and money flows between households and businesses.

natural resources the endowment of land and resources including air, water, soil, forests, fisheries, minerals, and ecological life-support systems

Figure 1.1 The Standard Circular Flow Model



and capital, continually regenerate through the economic circular flow process, but by what processes do natural resources regenerate for future economic use? Environmental economists recognize that it is necessary to address the limitations of the standard circular flow model in this respect. But ecological economists place a particular emphasis on a broader circular flow model that takes into account ecosystem processes as well as economic activity (Figure 1.2).

Taking this broader view, we notice that the standard circular flow diagram also omits the effects of wastes and pollution generated in the production process. These wastes, from both firms and households, must flow back into the ecosystem somewhere, either being recycled, through disposal, or as air and water pollution.

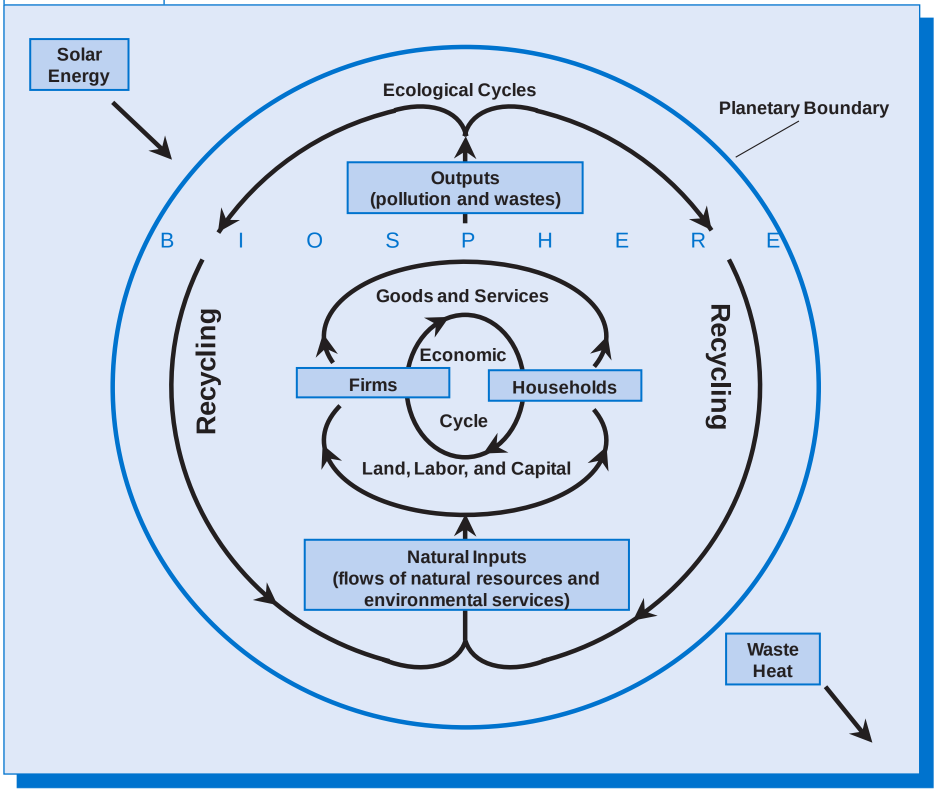
In addition to the simple processes of extracting resources from the ecosystem and returning wastes to it, economic activities also affect broader natural systems in subtler and more pervasive ways not illustrated in Figure 1.2. For example, modern intensive agriculture changes the composition and ecology of soil and water systems, as well as affecting nitrogen and carbon cycles in the environment.

Figure 1.2 provides a broader framework for placing the economic system in its ecological context. Natural resources include both renewable and nonrenewable resources. **Renewable resources** are those that are regenerated over time through ecological processes, such as forests and fisheries. Renewable resources can be managed sustainably if extraction rates don't exceed natural regeneration rates. However, if renewable resources are overexploited they can be depleted, such as species that go extinct through over-harvesting. **Nonrenewable resources** are those that do not regenerate through ecological processes, at least on a human time scale. Nonrenewable resources such as oil, coal, and mineral ores are ultimately available in a fixed supply, although new resources can be discovered to expand the known available supply. The other input into the economic system is solar energy, which as we will see later in the text provides a limited but incredibly abundant source of continual energy.

renewable resources resources that are regenerated over time through ecological processes, such as forests and fisheries, but can be depleted through exploitation.

nonrenewable resources resources that do not regenerate through ecological processes, at least on a human time scale, such as oil, coal, and mineral ores.

Figure 1.2 Expanded Circular Flow Model



What does this expanded circular flow model imply for economic theory? There are at least three major implications:

1. The recognition that natural resources and solar energy provide the essential input into economic processes implies that human well-being is ultimately dependent on these resources. Measuring well-being using standard economic metrics, such as gross domestic product, understates the importance of natural resources. This suggests a need for alternative indicators of well-being, which we will discuss in Chapter 10.
2. As shown in Figure 1.2, the ecological system has its own circular flow, which is determined by physical and biological rather than economic laws. This broader flow has only one net "input"—solar energy—and only one net "output"—waste heat. Everything else must somehow be recycled or contained within the planetary ecosystem.
3. In the standard circular flow model, the economic system is unbounded and can theoretically grow indefinitely. But in the expanded model, economic activity is limited by both the availability of natural resources and the ability of the environment to assimilate wastes and pollution. Thus the overall scale of the economy relative to the available natural resources must be considered.

As with some of the other questions we have discussed, there can be significant overlap between environmental and ecological economics perspectives on these issues. In terms of the double circular flow shown in Figure 1.2, a standard environmental economics perspective starts from the inner, economic, circle and tries to understand broader ecological issues in economic terms. Ecological economists place greater emphasis on the outer circle, with its biophysical laws and limitations, but are also aware of the importance of the way resources and the environment are taken into account in economic analysis.

Defining Sustainability

As mentioned in Box 1.1, sustainable development was first defined in 1987 by the United Nations' Brundtland Commission. Headed by the former Prime Minister of Norway, Gro Harlem Brundtland, the Commission published "Our Common Future," a nearly 400-page report on the environment and economic development. The report is generally recognized as coining the term **sustainable development**, and defining it as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

While sustainable development has become a popular buzzword, and nearly everyone agrees that it is a worthy goal, it is difficult to define precisely. Note that the Brundtland Commission defines sustainability based on the criterion of meeting human needs across time. However, this definition does not explicitly say anything about maintaining natural resources or ecological functions. This definition of sustainable development is consistent with standard environmental economics, which implies that at least some degradation of the environment can be acceptable as long as it doesn't interfere with meeting human needs.

sustainable development defined by the Brundtland Commission as development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

anthropocentric worldview a perspective that places humans at the center of analysis.

ecocentric worldview a perspective that places the natural world at the center of analysis.

An alternative, more ecologically-oriented, approach would define sustainability on the basis on maintaining appropriate levels of natural resources and ecological functions. In fact, some ecological economists believe that sustainability should be defined solely based on ecological, rather than human, factors. We will further discuss the different definitions of sustainability in Chapter 9.

Another way to characterize this distinction is that environmental economics tends to align with an **anthropocentric worldview**, meaning it places humans at the center of analysis. Thus the value of nature arises because humans assign it value. Ecological economics ascribes more to an **ecocentric worldview**, one that places the natural world at the center of analysis. An ecocentric viewpoint places value on nature independent of any human concerns.

A Pluralistic Approach

The final core concept in ecological economics is the promotion of a pluralistic approach to studying the relationship between the economy and the environment. By **pluralism** we mean the perspective that a full understanding of an issue, such as environmental problems, can only come from a variety of viewpoints, disciplines, and approaches. By promoting pluralism, many ecological economists distinguish themselves from more traditional environmental economists. The main academic journal for ecological economics, titled as you might expect *Ecological Economics*, notes that its:

pluralism the perspective that a full understanding of an issue can only come from a variety of viewpoints, disciplines, and approaches.

> unique and distinctive identity rests on its role in promoting a diversity of views and cross-disciplinary perspectives. [*Ecological Economics*] is based on the premise that understanding and managing the interplay between economic and ecological systems requires an interdisciplinary approach. [*Ecological Economics*] should therefore be a "big tent," not a narrow domain characterized by an exclusive or dominant viewpoint.[11]

One obvious implication of pluralism, as mentioned previously, is that many people who call themselves ecological economists were not primarily trained in economics. Even those who were primarily trained as economists are likely to have exposure to other disciplines, such as political science, engineering, and ecology, in addition to economics.

Embracing pluralism also means that ecological economists may disagree among themselves. As mentioned earlier, ecological and environmental economics have grown closer over time—not all ecological economists see this as a positive development. A 2013 article distinguishes between "shallow" and "deep" ecological economics. "Shallow" ecological economics is seen as closer to environmental economics, but deep ecological economics seeks

> to make ethical conduct central and to place the social, ecological and economic discourses on an equal footing. . . . Deep ecological economics requires challenging both personal and social pre-conceptions, while taking a campaigning sprit to change public policy and the institutions blocking the necessary transition to [alternative economic systems].[12]

This text will adopt a pluralistic approach to studying environmental issues, encompassing environmental economics, ecological economics, and other academic disciplines. The goal is to provide students with varied analytical approaches, allowing the reader to judge which approach or technique, or combination of approaches and techniques, is most useful in understanding a particular environmental issue, and in seeking policy solutions.

Other Differences between Environmental and Ecological Economics

As we saw earlier, environmental economists tend to favor attempts to place monetary values on environmental goods and services. In mainstream economics, something has **economic value** only if people are willing to pay for it. But if no one is willing to pay for a particular environmental good or service, then according to traditional environmental economics, it does not have economic value. For example, if no one is willing to pay to preserve an endangered insect in the Amazon forest, then there would be no loss of economic value if the species were to go extinct.

Analysts taking an ecological economics perspective are more likely to argue that environmental goods and services may have value separate from economic value, consistent with an ecocentric worldview. Specifically, ecological economists are more likely to acknowledge the **inherent value** of nature. Inherent value derives from ethics, rights, and justice, rather than human willingness to pay. Thus an insect species in the Amazon would have inherent value and a right to exist, and thus be worthy of preserving even if it does not have economic value. For a famous example advocating for the inherent value of the natural world, see Box 1.2.

economic value the value of something derived from people's willingness to pay for it.

inherent value the value of something separate from economic value, based on ethics, rights, and justice.

Box 1.2
SHOULD NATURE HAVE LEGAL RIGHTS?

In the late 1960s, the United States Forest Service granted a permit to the Disney Corporation to develop a large ski resort in the remote, undeveloped Mineral King Valley, adjacent to Sequoia National Park in California. The Sierra Club, an environmental organization, filed suit in federal court to block the development. The Forest Service and Disney responded that the Sierra Club did not have legal "standing" in the case—only a party that can demonstrate it will be sufficiently harmed by an action can initiate a lawsuit to prevent the action.

The question of whether the Sierra Club had legal standing in the case went all the way to the U.S. Supreme Court. While the Sierra Club technically lost the case, it is best known for the dissenting opinion written by Justice William Douglas. Douglas asserted that the real question wasn't whether the Sierra Club had legal standing, but that Mineral King Valley itself should have legal standing to sue for its own protection. Below is an excerpt from Douglas' opinion in the case:

> Inanimate objects are sometimes parties in litigation. A ship has a legal personality, a fiction found useful for maritime purposes. The corporation is an acceptable adversary and large fortunes ride on its cases. So it should be as respects valleys, alpine meadows, rivers, lakes, estuaries, beaches, ridges, groves of trees, swampland, or even air that feels the destructive pressures of modern technology and modern life.
>
> The voice of the inanimate object, therefore, should not be stilled. [B]efore these priceless bits of Americana (such as a valley, an alpine meadow, a river, or a lake) are forever lost or are so transformed as to be reduced to the eventual rubble of our urban environment, the voice of the existing beneficiaries of these environmental wonders should be heard.
>
> Those who hike the Appalachian Trail into Sunfish Pond, New Jersey, and camp or sleep there, or run the Allagash in Maine, or climb the Guadalupes in West Texas, or who canoe and portage the Quetico Superior in Minnesota, certainly should have standing to defend those natural wonders before courts or agencies, though they live 3,000 miles away. Then there will be assurances that all of the forms of life which it represents will stand before the court—the pileated woodpecker as well as the coyote and bear, the lemmings as well as the trout in the streams. Those inarticulate members of the ecological group cannot speak. But those people who have so frequented the place as to know its values and wonders will be able to speak for the entire ecological community.

Although the Sierra Club lost the case, public pressure forced the Disney Corporation to withdraw its development plans. In 1978 Mineral King Valley was added to Sequoia National Park and in 2009 it was designated as a wilderness area by the U.S. Congress, permanently protecting it from development.

Source: EarthJustice, "Mineral King: Breaking Down the Courthouse Door," http://earthjustice.org/features/mineral-king-breaking-down-the-courthouse-door; full opinions on Mineral King case http://caselaw.findlaw.com/us-supreme-court/405/727.html.

Both environmental and ecological economists recognize that policy recommendations should consider future costs and benefits. While we'll discuss this issue in more detail in Chapter 7, for now we can note that ecological economists are likely to place more weight on impacts that occur in the future, particularly those that occur more than a few decades in the future. Environmental economists favor weights that value impacts across time derived from market activity, while ecological economists often develop weights based on ethical considerations including the rights of future generations.

Table 1.1 Main Differences between Environmental and Ecological Economics

Question	Viewpoint of Environmental Economics	Viewpoint of Ecological Economics
How is the value of the environment determined?	Using economic value, based on people's willingness to pay.	Economic value may be useful, but also recognizes inherent values.
How are values measured?	Convert all values to monetary terms if possible.	Some values, particularly inherent value, cannot be expressed in monetary terms.
Advocate market-based solutions to market failures?	Yes, in the majority of cases.	Perhaps, but micro-level market solutions may fail to address macro-level issues.
Consideration given to future generations?	Some, with weights inferred from market activity.	More weight given to future generations based on ethical considerations.
Is value neutrality desirable?	Economics aims to be value neutral (objective).	Values are acceptable in a pluralistic framework.
What is sustainable development?	Maintaining the well-being of humans across time.	Maintaining ecological functions across time.
Are there ultimate limits to economic growth?	Perhaps not, at least in the foreseeable future.	Very likely, based on the limited availability of natural resources.

When market failures occur, environmental economists tend to advocate **market-based solutions**—policies that create economic incentives for behavioral changes, such as taxes and subsidies, without dictating what a firm or person can or cannot do. We will discuss market-based solutions in Chapter 8. While ecological economists aren't necessarily opposed to market-based solutions, at least in some situations, they emphasize that market-based solutions applied at a micro level fail to address macro-level issues about the overall scale of market activity. We will discuss this issue in more detail in Chapter 9.

market-based solutions policies that create economic incentives for behavioral changes, such as taxes and subsidies, without specific control of firm or individual decisions.

A final, related, point concerns whether further economic growth is possible, or even desirable. Mainstream perspectives support the idea that continued economic growth is feasible and generally desirable, although it should be tempered by greater application of market-based solutions for environmental externalities. Ecological economists are more likely to advocate for an eventual leveling-off of economic growth, or even "de-growth." We'll discuss this topic more in later chapters. Table 1.1 summarizes the main differences between environmental and ecological economics. The viewpoints of individuals who consider themselves one or the other may not exactly align with all these designations, but the table gives a sense of the contrasting perspectives that we will encounter as we explore environmental topics.

1.4 A LOOK AHEAD

How can we best use these two approaches to economic analysis of environmental issues? In the following chapters, we apply the tools and methods of each to specific environmental issues.

But first, Chapter 2 provides an overview of the relationship between economic development and the environment, looking at trends in developed and developing countries as well as envisioning sustainable development in both types of countries. The core theory and methods from environmental economics are explored in detail in Chapters 3–8. Chapters 9 and 10 further explore the concepts of ecological economics and environmental accounting.

In Chapters 11–20, we apply techniques of environmental and ecological economics to the major environmental issues of the twenty-first century: population, food supply, energy use, natural resource management, pollution control, and climate change. Chapters 21 and 22 bring together many of these topics to focus on questions of trade, economic development, and key institutions as they relate to the environment.

Summary

National and global environmental issues are major challenges in the twenty-first century. Responding to these challenges requires understanding the economics of the environment. Policies aimed at environmental protection have economic costs and benefits, and this economic dimension is often crucial in determining which policies we adopt. Some cases may require tradeoffs between economic and environmental goals; in other cases, these goals may prove compatible and mutually reinforcing.

Two different approaches address economic analysis of environmental issues. The standard approach applies economic theory to the environment using the concepts of monetary valuation and economic equilibrium. This approach aims to achieve efficient management of natural resources and the proper valuation of waste and pollution. The ecological economic approach views the economic system as a subset of a broader biophysical system. This approach emphasizes the need for economic activity that conforms to physical and biological limits.

Much of the analysis drawn from the standard approach is microeconomic, based on the workings of markets. Variations of standard market analysis can be applied to cases in which economic activity has damaging environmental effects or uses up scarce resources. Other economic analyses provide insight into the use of common property resources and public goods.

Ecological economics often takes a macro perspective, emphasizing the relationship between economic production and the major natural cycles of the planet. In many cases, significant conflicts arise between the operations of the economic system and these natural systems, creating regional and global problems such as global climate change from excess carbon dioxide accumulation. This broader approach requires new ways to measure economic activity, as well as analysis of how the scale of economic activity affects environmental systems.

This text outlines both analytical perspectives and draws on both to help clarify the major issues of population, food supply, energy use, natural resource management, and pollution. The combination of these analyses can help to formulate policies that can address specific environmental problems as well as promote a broader vision of environmentally sustainable development.

Key Terms and Concepts

anthropocentric worldview
common property resources
ecocentric worldview
ecological economics
economic value
environmental economics
externalities
inherent value

market-based solutions

market failure

natural resources

nonrenewable resources

pluralism

public goods

renewable resources

standard circular flow model

sustainable development

Discussion Questions

1. Do economic growth and sound environmental policy necessarily conflict? Identify some areas where a choice must be made between economic growth and environmental preservation and others where the two are compatible.
2. Is it possible to put a monetary price on environmental resources? How? Are there cases in which this is impossible? Identify specific instances of valuing the environment with which you are familiar or that you have read about.
3. What do you think are the strengths and weaknesses of the environmental economics approach? What are the strengths and weaknesses of the ecological economics approach?

Notes

1. See http://www.uncsd2012.org/content/documents/814UNCSD%20REPORT%20final%20revs.pdf.
2. UNEP, 2012, p. 5 and 23.
3. IPCC, 2014, p. 8.
4. United Nations, 2015.
5. Often the term "environmental and natural resource economics" is used instead of just "environmental economics" (as evident by the title of this book). Natural resource economics focuses on issues related to the allocation of natural resources, while environmental economics focuses on issues such as pollution, public goods, and the value of ecosystem services. For simplicity, we use the term environmental economics here, but this is inclusive of natural resource economics as well.
6. See Sandmo, 2015.
7. Howarth, 2008.
8. Plumecocq, 2014.
9. For example, see Hoepner *et al.*, 2012.
10. Baumgärtner and Quaas, 2010, p. 449. See also Remig, 2015.
11. Howarth, 2008, p. 469.
12. Spash, 2013, p. 359, 361. See also Söderbaüm, 2015.

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Web Sites

1. **www.worldwatch.org.** The homepage for the Worldwatch Institute, an organization that conducts a broad range of research on environmental issues. The Worldwatch annual "State of the World" report presents detailed analyses of current environmental issues.
2. **https://www.ncseglobal.org.** Web site for the National Council for Science and the Environment, with links to various sites with state, national, and international data on environmental quality.
3. **www.unep.org/geo/.** Web site for the Global Environment Outlook, a United Nations publication. The report is an extensive analysis of the global environmental situation.

CHAPTER

2

Resources, Environment, and Economic Development

Chapter 2 Focus Questions

- What is the relationship between economic growth and the environment?
- What are recent economic and environmental trends?
- Will economic growth encounter planetary limits?
- How can economic development become environmentally sustainable?

2.1 OVERVIEW OF ECONOMIC GROWTH

Human population and economic activity remained fairly stable during much of recorded history. Before the Industrial Revolution in the eighteenth and nineteenth centuries, the human population grew slowly and material living standards changed little. While data are limited, historical records suggest that in the 2,000 years prior to the Industrial Revolution world population grew from about 200 million to 1 billion. Average incomes changed even less during this period, from the equivalent of about \$500 per person annually to only about \$700.[1] In other words, economic growth was essentially non-existent prior to the Industrial Revolution.

The advent of the market economy and rapid technological progress, centered in Western Europe, altered this pattern dramatically. Population in Europe entered a period of rapid growth that led the British classical economist Thomas Malthus to theorize that populations would outgrow food supplies, keeping the mass of people perpetually at a subsistence standard of living.

Malthus's *Essay on the Principle of Population, as It Affects the Future Improvement of Society*, published in 1798, initiated a long and continuing debate on the impact of population growth and the availability of natural resources. History has proved the simple **Malthusian hypothesis** wrong: Although population in Western Europe more than doubled in the 100 years following the publication of Malthus's *Essay*, economic output per person grew at an even greater rate.[2] And on a global scale, population growth up to the present has been accompanied by rising living standards, despite significant inequality. But if we consider a more sophisticated argument, that a growing human population and economic system can eventually outrun their biophysical support systems, the debate turns out to have strong current relevance.

> **Malthusian hypothesis** the theory proposed by Thomas Malthus in 1798 that population would eventually outgrow available food supplies.

The debate over population growth is intimately intertwined with resource and environmental issues. In the twenty-first century, these issues, rather than the simple race between population and food supply, will strongly affect the course of economic development. It is unlikely that we will see major shortfalls in food supply on a global scale, although food crises resulting from rising prices have occurred, such as when average global food prices nearly doubled from 2007 to 2008.[3] But it is likely that the environmental stresses associated with a growing global population, in particular rising resource demands and waste generation, will require major changes in the nature of economic systems.

Measuring Growth Rates

In approaching complex issues of economic growth and the environment, we first need to define how economic growth has traditionally been measured by economists. **Gross domestic product (GDP)** is defined as the market value of final goods and services produced within a country's borders over a specified time period, usually a year. GDP can grow over time due to changes in two factors: population and per-capita (or per-person) GDP. In other words, we can define GDP using the simple identity:

> **gross domestic product (GDP)** the total market value of all final goods and services produced within a national border in a year.
>
> **GDP growth rate** the annual change in GDP, expressed as a percentage.

$$GDP = (population) \times (per\ capita\ GDP)$$

We can then define this identity in terms of growth rates, to show the relationship among the **GDP growth rate**, the **population growth rate**, and the **per capita GDP growth rate**:[4]

GDP growth rate = (population growth rate) + (per capita GDP growth rate)

We can use this equation to solve for one of these three variables when we know the other two. For example, suppose the population of a country increased by 10 percent during some time period, and that the country's GDP grew by 14 percent during this same period. We can then conclude that GDP per capita grew by 4 percent.

To correct for the effects of inflation, we should use **real GDP** rather than **nominal GDP** in this equation. Real per capita GDP will rise steadily, as long as real GDP grows at a consistently higher rate than population. For this to occur, economic productivity must also rise steadily. This increasing productivity is, of course, the key to escaping the Malthusian trap.

Increased agricultural productivity means that the portion of the population working in farming can decrease, freeing labor for industrial development. Increased industrial productivity brings higher living standards, measured in traditional economic terms as growth in real GDP per capita. Broadly speaking, economic development has unfolded along these lines in Europe, the United States, and other industrialized countries.

population growth rate the annual change in the population of a given area, expressed as a percentage.

per capita GDP growth rate the annual change in per capita GDP, expressed as a percentage.

real GDP gross domestic product corrected for inflation using a price index.

nominal GDP gross domestic product measured using current dollars.

Factors Essential to Economic Growth

How is steady growth in productivity and GDP per capita possible? Standard economic theory identifies two sources of increased productivity. First is the accumulation of capital. Recall our discussion of the standard circular flow model from Chapter 1—capital is one of the three standard factors of production, along with labor and land. With investment the stock of capital can increase over time, which tends to increase the productivity of workers. Second, technological progress raises the productivity of capital, labor, and land. Standard economic growth models place no limits on this process. Provided that investment continues at adequate rates and technology keeps improving, productivity and GDP per capita can continue rising far into the future.

The ecological economics perspective focuses on three other factors as essential to economic growth. The first is energy supply. Europe's economic growth in the eighteenth and nineteenth centuries depended heavily on coal as an energy source, and some writers at the time expressed concern that coal supplies might run out. In the twentieth century, oil displaced coal as the prime energy source for industry.

Currently oil, natural gas, and coal provide over 80 percent of energy supplies for both developed and developing nations.[5] To a great extent, economic growth in both agriculture and industry has been a process of substituting fossil-fuel energy for human labor. This substitution has important resource and environmental implications, which in turn affect projections of future economic growth.

The second fundamental factor is supplies of land and natural resources. As mentioned in Chapter 1, economists have traditionally referred to "land" to account for the productive resources of nature. Ecological economists prefer the term **natural capital** to refer more broadly to the natural endowment of land and resources, including air, water, soil, forests, minerals, and ecological life-support systems. All economic activities require some natural capital to provide raw materials, whether it is the wood to make furniture, the land

natural capital the available endowment of land and resources, including air, water, soil, forests, fisheries, minerals, and ecological life-support systems.

to grow crops, or the fish to make a meal. When economic development is at a low level, natural capital may seem abundant. But as economic activities expand, natural capital may not be sufficient to meet all needs. This may lead to conflicts, such as when housing competes with farming for rural land, or when road-building makes land less suitable for residential or agricultural use. Eventually, degradation or depletion of natural capital could constrain future economic growth.

Land, of course, is fixed in supply. Except in very limited areas, such as the diked areas of the Netherlands, human technology cannot create more land. Natural resources vary in abundance, and human ingenuity may discover new resources or new uses for existing resources, but both mineral resources and the regenerative capacity of forests and other living resources have physical limits.

The third important factor emphasized by ecological economists is the **absorptive capacity of the environment** to assimilate wastes and pollution. This issue is not so critical when the scale of economic activity is small relative to the environment. But as national and global economic activity accelerates, the flow of waste products increases and may threaten to overwhelm environmental systems. Flows of solid wastes, sewage and liquid wastes, toxic and radioactive wastes, and atmospheric emissions all pose specific environmental problems that require local, regional, and global solutions.

absorptive capacity of the environment the ability of the environment to absorb and render harmless waste products.

2.2 ECONOMIC GROWTH IN RECENT DECADES

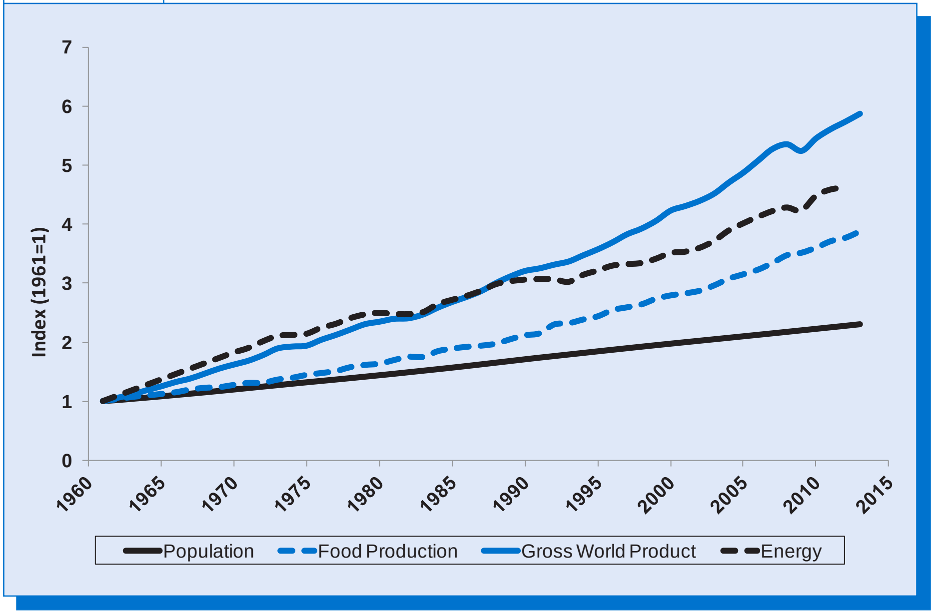
We next consider the history of economic growth, and its relation to issues of natural resources and the environment. Figure 2.1 tracks the history of several key variables since the 1960s. All variables are indexed to 1961, meaning that the value of each variable is scaled to equal 1.0 in 1961, and then the value for future years is expressed relative to the 1961 value. For example, the world population was 3.1 billion in 1961 and had risen to 6.2 billion in 2001. So the indexed population value for 2001 is 2.0, meaning it is twice as large as the 1961 value.

The trends in Figure 2.1 tell a clear story that significant economic progress has been made over the last 50 years. The growth rates for food production, economic production, and energy use have all been greater than the rate of population growth. Thus, relative to 1961 the average person has access to more food, more economic production, and more energy.

Other measures of human well-being over this time period also indicate positive global trends. For example, life expectancy increased from 53 to 71 years over this period. Literacy rates have improved, and access to clean water and adequate sanitation facilities has expanded. Thus it seems that, at least so far, resource constraints have generally not been sufficient to hamper economic progress.

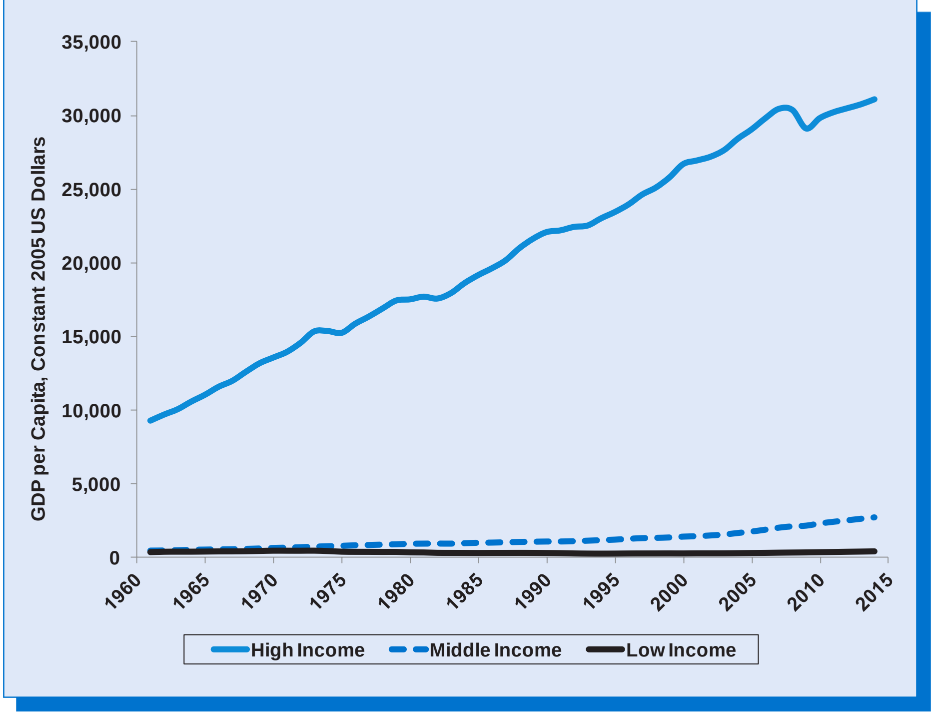
Figure 2.1 presents average results for the entire world. But economic and social conditions can vary tremendously across countries. We don't know from looking at Figure 2.1 if the overall picture of progress applies to both rich and poor countries. In Figure 2.2 we divide countries into three categories based on income levels—high, middle, and low.[6] We see that average income levels in the high-income countries have increased (after an adjustment for inflation) from about $10,000 to $30,000 per capita over the last several decades. Income growth measured in percentage terms has been highest in the middle-income countries, mainly due to economic growth in China and India. Averaged over all middle-income countries, incomes grew from about $500 per person to more than $2,700. But economic progress in low-income countries has been negligible. Average incomes were only about $420 per person in 2014, essentially unchanged from the early 1960s.

Figure 2.1 Growth in Population, Food Production, Economic Production, and Energy Use, 1961–2013



Sources: Population, food production, and gross world product from the World Bank, World Development Indicators database; energy data from the U.S. Energy Information Administration, International Energy Statistics.

Figure 2.2 Economic Growth, 1961–2014, by Country Income Category



Source: World Bank, World Development Indicators database.

The data in Figure 2.2 demonstrate the extent of global economic inequality. But the results also suggest that we may need to approach our study of the relationship between economic development and the environment differently in developed versus developing countries. Economic growth has been substantial in high- and middle-income countries—can such growth continue without depleting important categories of natural capital or over-loading the absorptive capacity of the environment? For low-income countries, is there a relationship between their very low average growth rates and the environment?

resource curse hypothesis the theory that countries or regions with abundant natural resources actually grow more slowly than those where natural resources are scarcer.

Until recently, an abundance of natural resources was generally considered to be a key ingredient in successful economic development. But in the last few decades economists have explored the **"resource curse" hypothesis**—that countries or regions with abundant natural resources actually grow more slowly than those where natural resources are scarcer. This hypothesis was first comprehensively tested in a 1995 paper which concluded that

> [based on analysis of 97 countries] economies with a high ratio of natural resource exports to GDP [initially] . . . tended to have low growth rates during the subsequent period. This negative relationship holds true even after controlling for variables found to be important for economic growth, such as initial per capita income, trade policy, government efficiency, investment rates, and other variables.[7]

But the resource curse hypothesis is not universally accepted, as recent analyses have both supported and refuted the hypothesis.[8] We will explore this topic further toward the end of the book.

2.3 ENVIRONMENTAL TRENDS IN RECENT DECADES

As mentioned in Chapter 1, every few years UNEP publishes *Global Environmental Outlook (GEO)* reports that assess global environmental conditions and document trends. The most recent report when this book was written, GEO-5 published in 2012, discusses the "great acceleration" of human impacts on the environment starting around 1960. In this section we draw upon the GEO reports and other sources to present an overview of environmental trends. Similar to our overview of economic trends, we will take a global perspective toward environmental trends, but also consider how these trends vary between high- and low-income countries.

The GEO-5 report includes separate chapters on five categories of environmental impacts:

1. Atmosphere
2. Land
3. Water
4. Biodiversity
5. Chemicals and Waste

While we will present data below on each of these trends separately, the report emphasizes that the earth is a complex system with interacting components. Further, the underlying drivers of diverse environmental impacts are related. At a simplified level, nearly all of the great acceleration of human impacts can be linked to expansion of both the human population and economic activity. Therefore, a piecemeal approach to solving separate environmental problems is generally not effective. The good news is that well-designed economic policies can address multiple environmental issues. The less-encouraging news is that such comprehensive policies tend to be more difficult to enact from a political perspective than targeted policies. We will spend considerable time throughout this text discussing policy options, including both market-based policies and other alternatives.

Atmosphere Impacts

Trends in emissions into the atmosphere can be broadly classified into two categories: those related to greenhouse gases (i.e., those that contribute to climate change) and those related to other air pollutants. GEO-5 concludes that

> climate change is the most important atmospheric issue. While there is considerable concern about this complex problem, progress has been slow due to varying levels of motivation and because some low-carbon technological solutions are considered expensive. Despite attempts to develop low-carbon economies in a number of countries, atmospheric concentrations of greenhouse gases continue to increase to levels likely to push global temperatures beyond the internationally agreed limit of 2°C above the pre-industrial average temperature.[9]

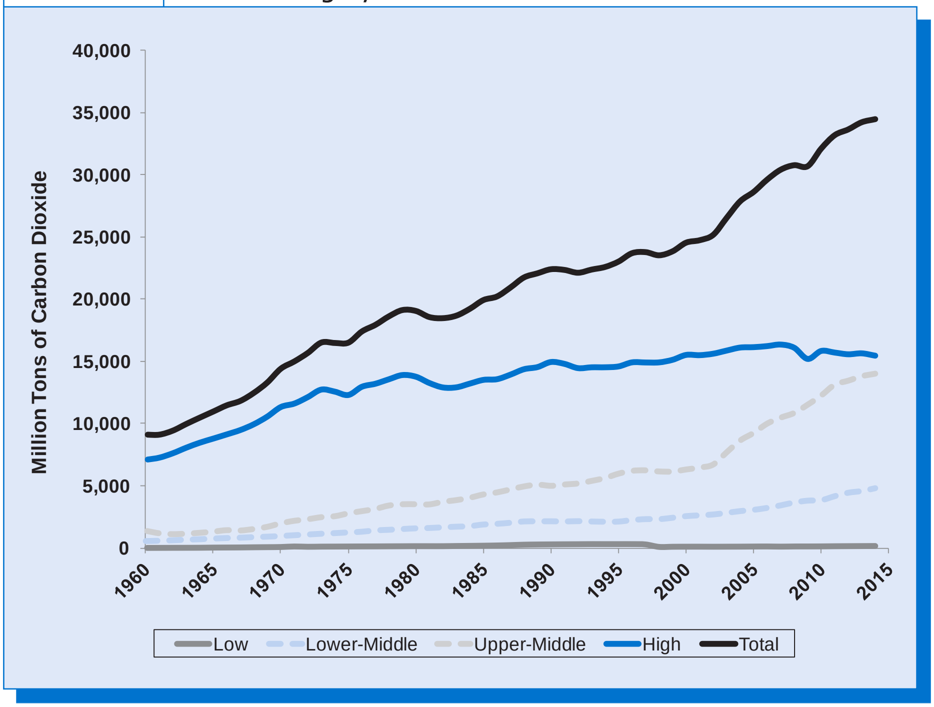
The primary greenhouse gas is carbon dioxide (CO_2). Figure 2.3 shows the global emissions of CO_2 since the 1960s, with emissions steadily rising up to 2014.[10] But looking at the data in Figure 2.3 by income group again tells a more informative story. First, we can see that the carbon emissions of the world's poorest countries are negligible. Second, until recently the majority of global emissions were attributed to the high-income countries. Prior to 1990 at least two-thirds of global emissions were from high-income countries. Since then, emissions from high-income countries have grown slowly—only increasing by about a total of 3 percent between 1990 and 2014.

The most rapid increase is in emissions by upper middle-income countries, including China—up 180 percent since 1990. Emissions have also increased significantly in lower middle-income countries, about 120 percent since 1990, primarily as a result of emissions growth in India. As a result of these trends, CO_2 emissions from high-income countries now comprise less than half of the global total. Further, most of the projected future growth in emissions will occur in the developing world. Clearly, as we'll discuss in more detail in Chapters 12 and 13, an effective response to climate change will require a coordinated international response.

The trends for other air pollutants offer a mix of policy successes and ongoing challenges. Figure 2.4 shows global trends since 1900 for three major air pollutants: sulfur dioxide (SO_2), nitrogen oxides (NO_x), and volatile organic compounds (VOC). Emissions of all three chemicals increased significantly from 1940 to 1980. But since then, emissions of SO_2 have declined by about 20 percent, and the growth in NO_x and VOC emissions has slowed.

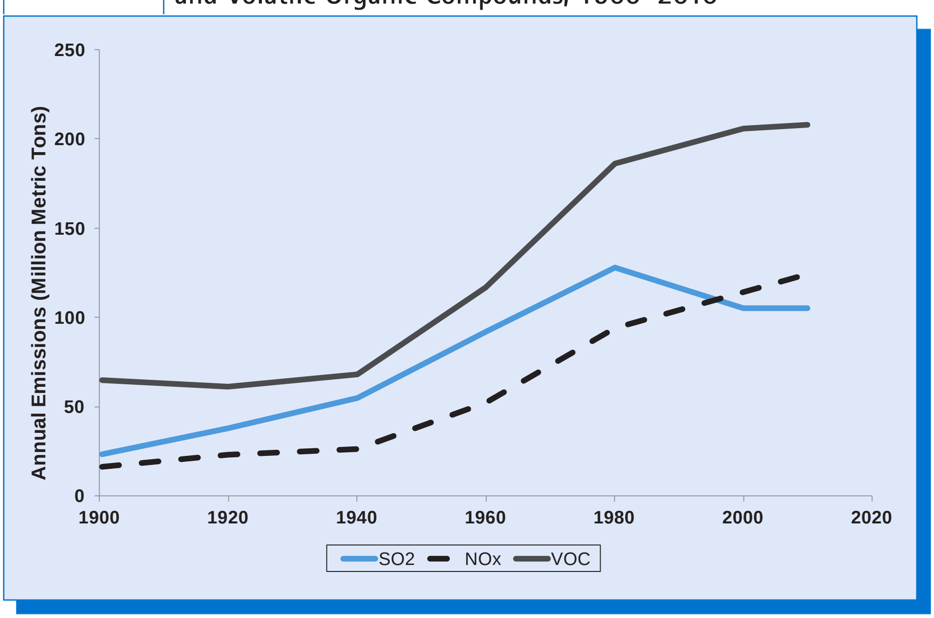
Once again, the trends differ in developing and developed countries. In North America and Europe, emissions of all three chemicals have declined over the last few decades, with further reductions projected for the future. But in both East Asia (which includes China) and South Asia (which includes India) the emissions of all three chemicals have continued to increase recently, with projections showing further increases or, at best, a leveling off of emissions.

Figure 2.3 Global Carbon Dioxide Emissions, 1960–2014, by Country Income Category



Source: Carbon Dioxide Information Analysis Center, Global Carbon Project, National Emissions v1.1 (December 2015). Income categories obtained from the World Bank's Country and Lending Groups for fiscal year 2016.

Figure 2.4 Global Emission Trends for Sulfur Dioxide, Nitrogen Oxides, and Volatile Organic Compounds, 1900–2010



Source: HTAP, 2010.

Box 2.1
HEALING THE OZONE LAYER

The earth's ozone layer, located in the stratosphere about 20 to 30 kilometers above the earth, provides protection from most of the sun's ultraviolet (UV) radiation. By blocking 97–99 percent of incoming UV radiation, the ozone layer effectively reduces the damaging effects of UV rays, such as immune system suppression and skin cancer.

Starting in the 1970s, scientists began to assert that the emissions of various chemicals into the atmosphere could deplete the ozone layer, mainly chlorofluorocarbons (CFCs) which were used as refrigerants, in aerosol sprays, and as cleaning agents. Initially, the chemical companies producing CFCs refuted the scientific claims, arguing that their chemicals were safe. But in the mid-1980s scientists discovered an "ozone hole" over Antarctica, where concentrations of ozone had fallen far more than anticipated. This helped galvanize the call for regulation of CFCs and other ozone-depleting substances (ODSs).

In 1987 the Montreal Protocol treaty was drafted to schedule an international phase-out of CFCs and other ODSs. The Protocol eventually became the first United Nations treaty to be ratified by all member nations. Subsequent revisions to the Protocol actually increased the pace of the phase-out, particularly in developed nations. Often working in cooperation with environmental groups such as Greenpeace, chemical companies have developed alternatives to CFCs that are not harmful to the ozone layer.

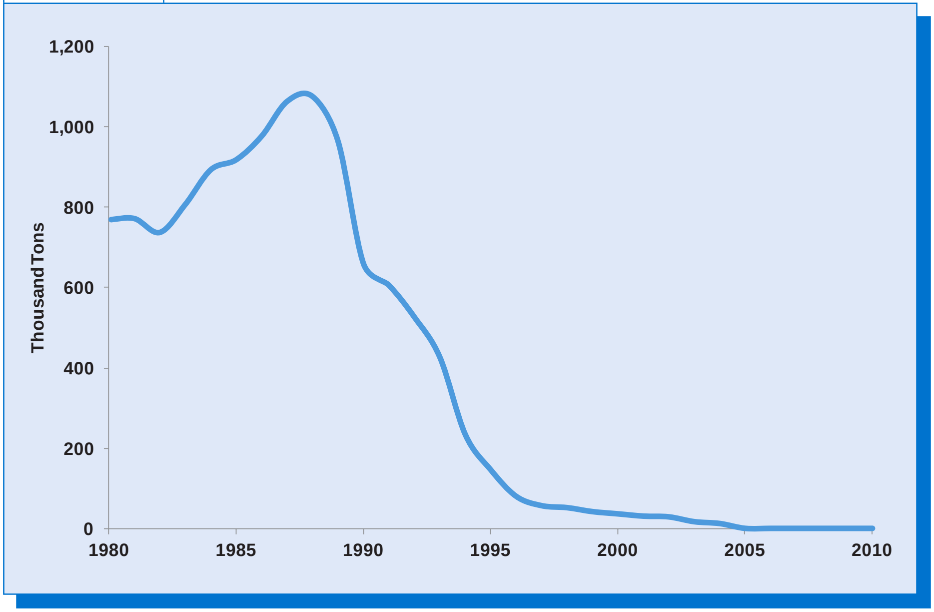
As shown in Figure 2.5, global production of CFCs declined dramatically after ratification of the Montreal Protocol. By 2005, CFC production had essentially ceased. Phase-outs of other ODSs have also either been completed or are underway.

ODSs are long-lived in the atmosphere, with some persisting for 100 years or more. Thus, despite the Montreal Protocol, the ozone layer initially continued to deteriorate. A 2014 assessment by the World Meteorological Organization and the United Nations concludes that the ozone layer has remained relatively stable since 2000, with a small increase in ozone concentrations in recent years. The study estimates that the ozone layer should fully recover before 2050 in most parts of the world, and then somewhat later for the Antarctic ozone hole.[13] Based on these results, former Secretary-General of the United Nations Kofi Annan has called the Montreal Protocol "perhaps the single most successful international agreement to date."[14]

Indoor air pollution actually causes more deaths globally than outdoor air pollution. According to the World Health Organization over 4 million people per year die from indoor air pollution, predominantly in low- and middle-income countries where people use wood, coal, or dung as their primary cooking fuel.[11] The GEO-5 report concludes that "little to no progress" has been made in reducing indoor air pollution in poor rural areas of the world where poverty remains a barrier toward the adoption of cleaner cooking fuels.

Two particular success stories stand out in reviewing the trends on air pollution. First, lead pollution has been dramatically reduced in developed nations. Lead inhalation can impede the neurological development of children and cause cardiovascular impacts, such as high blood pressure and heart disease, in adults. Mainly as a result of banning lead in gasoline, lead pollution in the United States declined by 92 percent from 1980 to 2013.[12] For another major atmospheric success story, see Box 2.1.

Figure 2.5 Global Production of Chlorofluorocarbons, 1980–2010



Source: Alternative Fluorocarbons Environmental Acceptability Study, www.afeas.org/index.html.

Land Impacts

In summarizing recent human impacts on land resources, GEO-5 takes a perspective that aligns with our expanded circular flow model from Chapter 1. The report notes that

> many terrestrial ecosystems are being seriously degraded because land-use decisions often fail to recognize noneconomic ecosystem functions and biophysical limits to productivity. For example, deforestation and forest degradation alone are likely to cost the global economy more than the losses of the 2008 financial crisis. The current economic system, built on the idea of perpetual growth, sits uneasily within an ecological system that is bound by biophysical limits.[15]

According to a 2002 analysis, the impacts of humans are evident on 83 percent of the world's total land area, and 98 percent of the land area where it is possible to grow major crops.[16] The two largest categories of human land impacts are agriculture and forestry.

There are nearly 5 billion hectares of land, about 40 percent of the world's total land area, devoted to growing crops or pastureland for raising animals. Total global agricultural area has remained relatively constant since the 1960s, but crop production has increased by a factor of 3.7.[17] In other words, the same amount of agricultural land produces, on average, nearly four times the harvest as it did 50 years ago. The increase in crop production has been greatest in middle-income countries, where yields have grown by a factor of 5.3. Agricultural gains have also been substantial in low-income countries.

As we saw in Chapter 1, the human population is projected to grow to nearly 10 billion by 2050. Can agricultural yields be expanded even further? A 2010 analysis concludes that there is considerable potential to increase yields.[18] The current production efficiency of wheat is estimated to be only 64 percent of its global potential. The efficiency of corn production is even lower—only 50 percent of its potential. The reason is that crop production techniques in much of the developing world do not utilize modern practices. However, widespread implementation of these practices, namely increased use of fertilizers, pesticides, and irrigation water, can have negative environmental consequences. We will discuss agriculture and its environmental impacts in more detail in Chapter 16.

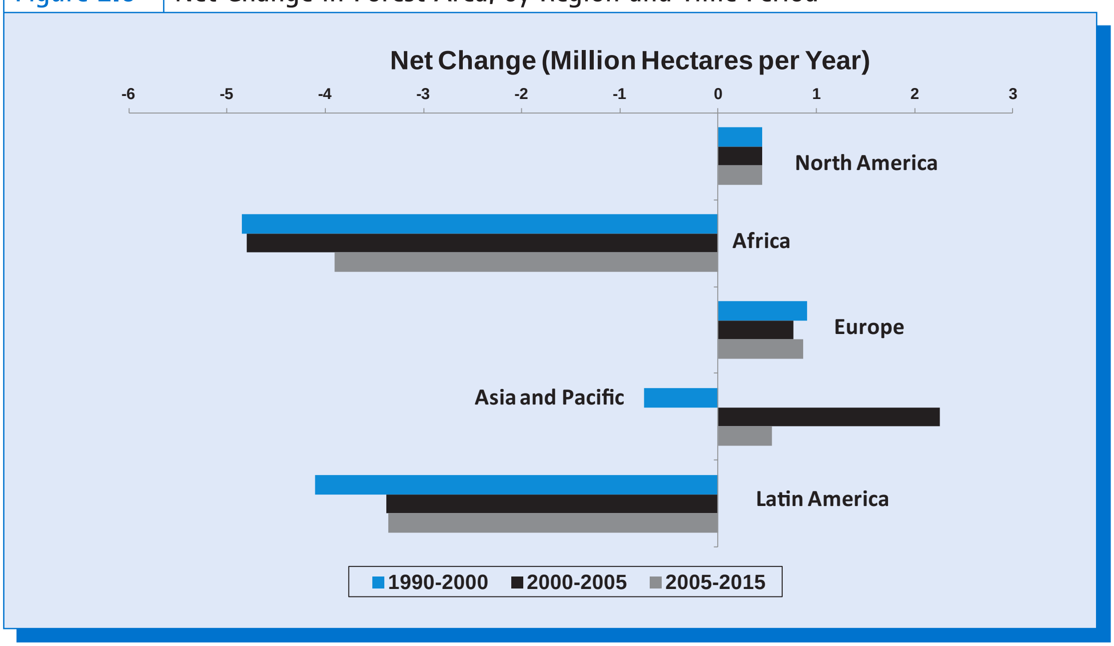
Forests cover 31 percent of the world's land area. The rate of global deforestation has slowed since the 1990s, with annual forest loss declining from 16 million to 13 million hectares. But as Figure 2.6 shows, forest trends vary dramatically in different parts of the world. The figure shows the annual net change in total forest area in different regions over three time periods: 1990–2000, 2000–2005, and 2005–2015. In North America and Europe, forest area has increased during all three time periods. In Asia and the Pacific, net deforestation occurred during the 1990s, but reforestation has been the norm since then, particularly during the 2000–2005 period. Most of this reforestation is a result of massive tree planting in China, where an estimated 66 billion trees have been planted in recent decades.[19] Significant deforestation is occurring in Latin America (including the Amazon Forest in Brazil) and Africa, although recently at lower rates than during the 1990s. We will discuss forestry issues in more detail in Chapter 19.

Water Impacts

While water is a resource that is renewed through natural processes, only a limited amount is available for human use at one time. Also, pollution can make a water source unusable for a particular activity, such as drinking or fishing. The availability of water varies significantly across the world—while water is abundant in some areas, it is quite scarce in others.

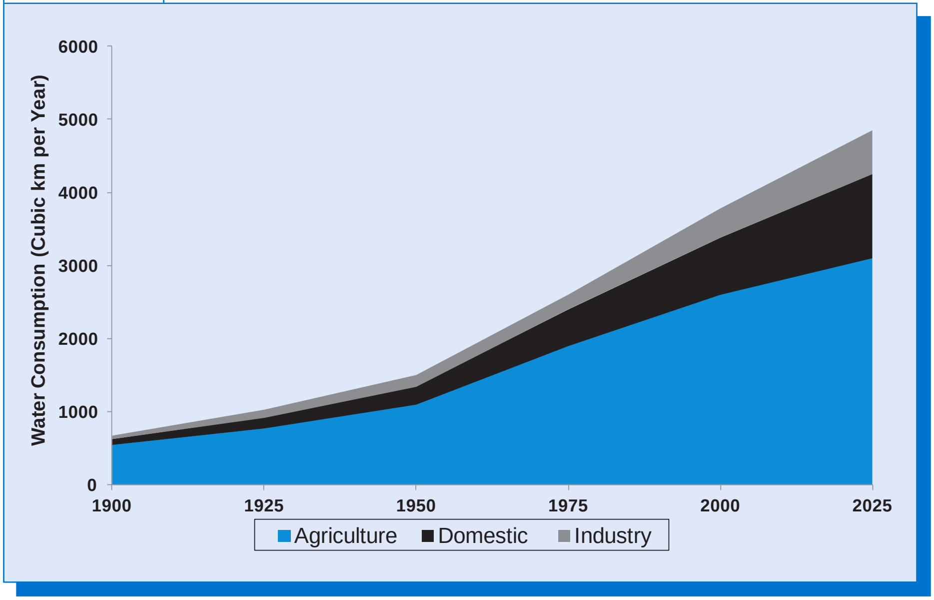
Global water use increased by more than a factor of five during the twentieth century, with further increases projected in the future (Figure 2.7). The majority of global water use

Figure 2.6 Net Change in Forest Area, by Region and Time Period



Source: UNEP, 2012.

Figure 2.7 Global Water Extraction, 1900–2025, by Use



Source: UNEP, 2008.

is for agricultural purposes. GEO-5 notes that increasing water use efficiency, particularly for irrigation, is critical to ensure that water resources are used sustainably.

Many countries are becoming increasingly dependent upon groundwater, which is essentially a nonrenewable resource. For example, India has increased its groundwater withdrawals by a factor of 10 since 1960, and China has also significantly expanded its use of groundwater.[20] Some countries in the Middle East, including Qatar, Saudi Arabia, and the United Arab Emirates, obtain 95 percent or more of their total water supply from groundwater.[21] In most places of the world, extraction of groundwater is essentially unregulated, meaning that farmers and other users are able to pump all they want.

The health of the world's oceans is another important water issue. One problem is the accumulation of litter in certain parts of the ocean. In 2011 the U.S. Environmental Protection Agency called for further research on the impacts of plastic debris in marine ecosystems, particularly in the Pacific Ocean.[22] Climate change likely poses the greatest threat to ocean ecosystems. In addition to warmer water temperatures, the build-up of carbon in oceans makes them more acidic. Coral reefs are particularly vulnerable to acidification. A 2012 analysis found that preserving more than 10 percent of the world's coral reefs would require limiting global warming to no more than 1.5°C above pre-industrial levels, even more ambitious than the agreed-upon target of 2°C.[23]

Biodiversity Impacts

All of the impacts discussed above—air pollution and climate change, as well as the degradation of land and water habitats—are causing what some researchers consider to be an extinction crisis on scale with previous mass extinctions, such as the one that killed off the dinosaurs 65 million years ago.[24] GEO-5 notes that:

> The state of global biodiversity is continuing to decline, with substantial and ongoing losses of populations, species and habitats. For instance, vertebrate populations have declined on average by 30 per cent since 1970, and up to two-thirds of species in some taxa are now threatened with extinction. Declines are most rapid in the tropics, in freshwater habitats and for marine species utilized by humans.[25]

The most significant threats to vertebrate species are, in order of significance: agriculture/aquaculture, logging, and urban development. In the future these threats are likely to be overtaken by the impacts of climate change. According to one analysis in the prestigious scientific journal *Nature*, under a mid-range climate scenario 15–37 percent of species would be "committed to extinction" by 2050.[26] A 2015 paper finds that the percentage of species that will become extinct due to climate change would only be 5 percent if the 2°C target is met, but 16 percent under a business-as-usual scenario.[27]

As discussed in Chapter 1, analyses by environmental economists tend to focus on the economic benefits of species, while ecological economists are more likely to argue for species preservation on the basis of ethical standards, inherent values, and the need to maintain diverse, resilient ecosystems to support both planetary and human health and well-being. However, as we will see in Chapter 9, many ecological economists have also recognized that economic policies can be effectively used to preserve biodiversity.

Chemicals and Waste

Of the five impacts we are summarizing in this chapter, the impacts of chemicals and waste on the environment are perhaps the least understood. According to GEO-5:

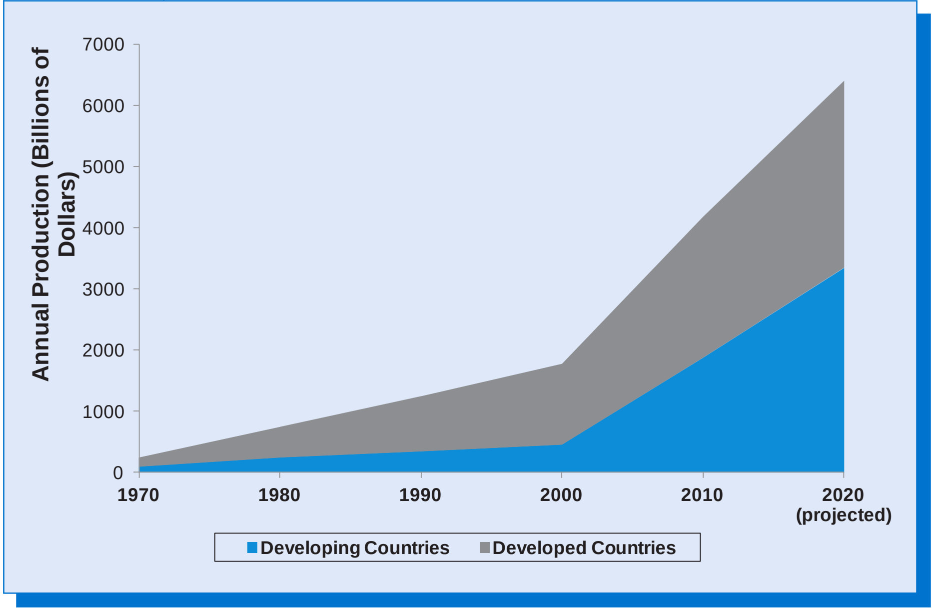
> There is an extensive but incomplete body of scientific knowledge on the impacts of chemicals and wastes on humans and the environment, with particular information and data gaps on the uses, emissions, exposure pathways and effects of chemicals. Global understanding of the complexity of properties and environmental impact of chemicals and wastes is therefore markedly deficient.[28]

The global chemicals industry has expanded significantly in recent decades, with annual production growing from less than $200 billion in 1970 to more than $4 trillion by 2010 (Figure 2.8).[29] Prior to 2000, chemicals production took place primarily in developed nations. But since then production has shifted to developing countries, with China now being the world's largest producer. Some data suggest that chemicals use is slightly declining in developed countries, although trends vary across countries.[30]

Approximately 250,000 chemicals are commercially available. However, little data are available on the environmental impacts of the vast majority of chemicals. We do know that chemicals are widely distributed throughout ecosystems—for example, more than 90 percent of water and fish samples worldwide show evidence of pesticides. Estimates of human health impacts from chemicals exposure are incomplete, particularly in developing countries. Those living in poverty are generally subjected to more exposure to chemicals, with children particularly vulnerable.

The generation of waste is also increasing significantly. According to the World Bank, the amount of municipal waste generated per-person doubled worldwide from 2002 to 2012, with further increases projected for the future.[31] Waste generation is generally higher in richer countries. But once again, projections suggest that most of the increase in waste in the future will be a result of economic development in low- and middle-income countries.

Figure 2.8 Growth of Chemicals Production Industry, 1970–2020



Source: UNEP, 2013.

About half of all waste generated worldwide is disposed of in landfills. Close to 20 percent of waste is recycled, and 15 percent is incinerated to produce energy. The disposal of waste is a major public health concern in many low- and middle-income countries where wastes are discarded in open dumps near slums. People who then pick through these dumps for valuable items are often exposed to medical and hazardous wastes. A growing concern in recent years is exposure to electronic waste—see Box 2.2 for more on this issue. We will also discuss waste and recycling further in Chapter 17.

2.4 OPTIMISTS AND PESSIMISTS

What can we conclude from our brief overview of economic and environmental trends? Do these trends provide a reason to be optimistic or pessimistic about the future?

There are no simple, clear-cut answers to these questions. One may reach an optimistic conclusion based upon the evidence of continued, although unequal, economic and human development, with increasing per capita food consumption and living standards refuting the simple Malthusian hypothesis. But on the other hand, negative environmental impacts have generally increased, including global impacts such as climate change, species loss, and ocean pollution, as well as local and regional impacts such as deforestation, depletion and pollution of water supplies, and buildup of toxic wastes. Pessimists point out that just because major environmental catastrophes have been, for the most part, avoided so far, there is no assurance that we can assume the future will be similar. And looking ahead, climate change presents humanity with perhaps its greatest, and most complex, environmental challenge.

Debate is ongoing concerning the resource and environmental factors that contribute to, and could eventually limit, economic growth. In 1972 a Massachusetts Institute of

Box 2.2
E-WASTE

The global generation of electronic waste (e-waste), including computers, cell phones, small and large appliances, and televisions, is increasing exponentially, especially in developing countries. According to the United Nations, the number of cell phones sold in China will increase by a factor of 7 between 2007 and 2020, and by a factor of 18 in India.[32]

The disposal of e-waste is of particular concern because these products contain small amounts of commercially valuable metals, including silver, palladium, and gold, along with dangerous substances such as lead and dioxin. Thus, when scavengers access e-waste they may expose themselves to toxins in the process of extracting the salable components. Also, toxic chemicals can leach into water supplies or be released into the air.

The majority of e-waste is generated in developed nations, but much of this waste is exported—often illegally—to developing countries. One of the world's largest e-waste dump sites is the Agbogbloshie site in Ghana. It is estimated that 40,000 people in the area are being exposed to toxic chemicals. Soil samples in the area contained lead levels over 18,000 parts per million (ppm) while the allowable level of lead in soil in the United States is only 400 ppm.[33]

Efforts are underway to ensure that e-waste is properly recycled or safely disposed of. In 2014 the European Union instituted a new directive on waste for electrical and electronic equipment. The goal of this legislation is to increase the portion of e-waste properly treated from about one-third to 85 percent by 2019. Shops selling electronic products are required to accept smaller e-waste items, while manufacturers are required to accept larger items for recycling. Other provisions encourage the reuse of products and design improvements that avoid the use of toxic chemicals.[34]

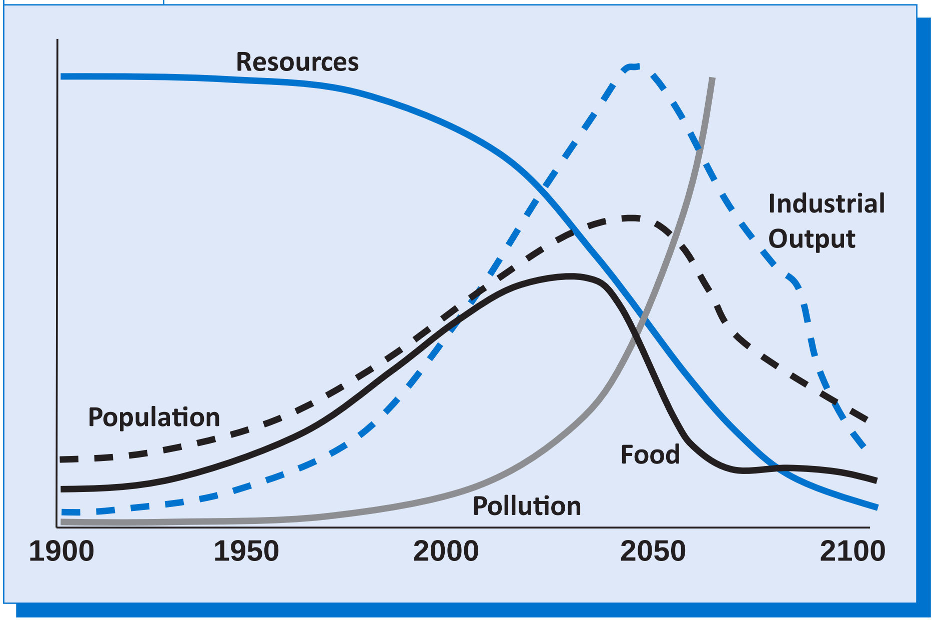
Technology research team published a study titled *The Limits to Growth*, which used computer modeling to estimate future global trends for five key variables: pollution, industrial output, population, food, and resources. The model's basic conclusion was that continuing along a business-as-usual path, without major policy or behavioral changes, would deplete available resources, leading to a significant decline in industrial output and food supplies, starting around 2020, followed by a declining population.

The authors revised their model in 2004, reaching the same conclusion of eventual collapse under a business-as-usual scenario but pushing back the onset by a decade or two, as shown in Figure 2.9. We see that resource depletion, which started in the twentieth century, continues throughout the twenty-first century. As population, food production, and industrial output increase in the early twenty-first century, pollution skyrockets. By the middle of the twenty-first century, a reduction in food, industrial output, and population is underway, with further declines later in the century.

The authors emphasize that collapse is not inevitable. They also model a "sustainable world" scenario where average family size is two children, modest limits are put on material production, and society invests heavily in sustainable technologies. Their results under this scenario show the human population stabilizing at less than 8 billion, with industrial output also stabilizing and pollution eventually decreasing.

The results of *The Limits to Growth* models have been criticized as overly pessimistic, akin to the original Malthusian hypothesis which under-estimated the potential of technological improvements.[35] Critics also contend that while nonrenewable resources are being depleted

Figure 2.9 The Limits to Growth Model, Business-As-Usual Scenario



Source: Meadows *et al*., 2004.

in an absolute sense, new discoveries and more efficient use of resources mean that resource depletion is insufficient to cause a Malthusian crash in the foreseeable future. Supporters of the limits-to-growth model emphasize that the actual data have generally tracked the projections of the business-as-usual model.[36] They also note that the critical point is not whether new resources can be discovered but whether resources can be extracted at a rate to meet growing demands without unacceptable environmental damage.

In this text we do not offer a definitive opinion on future trends, but later chapters will provide extensive information to develop informed opinions about the future. The focus of this book is on assessing policy options, rather than promoting a particular viewpoint. While analysts differ greatly regarding appropriate policy responses, few dispute the importance of global environmental and resource issues. As we will see, both a market-oriented approach stressing economic system adaptability and an ecological approach stressing biophysical systems and constraints have important roles to play in devising policy responses.

Chapters 11–20 give various environmental and resource problems detailed attention. Although in each case specific policies may address individual problems, the issues together suggest a common need for a different kind of economic analysis, one that addresses a global economy in which resource and environmental considerations are much more prominent than in the past.

Rather than approaching environmental questions as a secondary issue after we have dealt with the basic economic issues of production, employment, and output growth, both environmental and ecological economists recognize that economic production is ultimately linked to the quality of the environment and the availability of natural resources. This becomes only more evident as the scale of economic production increases. While environmental and ecological economists may define sustainable development differently, both assert that policy changes are necessary in order to achieve truly sustainable outcomes. We now turn to a more detailed discussion of sustainable development, and what its policy implications are for various environmental issues.

2.5 SUSTAINABLE DEVELOPMENT

Recall that the standard view of economic growth is defined in terms of per capita GDP, meaning that total GDP must grow faster than population. Sustainable development, for both environmental and ecological economists, is about more than simply keeping GDP, or GDP growth rates, above a particular level. Thus we need new measures of human and ecological well-being in order to determine whether outcomes are sustainable. Environmental economists emphasize the maintenance of human well-being—something that is dependent on more than GDP, such as the quality of the environment, the availability of leisure time, and the fairness of political systems. Ecological economists emphasize the maintenance of the ecological base of the economy—fertile soils, natural ecosystems, forests, fisheries, and water systems—factors that are generally excluded from GDP. As we will see in Chapter 10, various metrics have been developed that either adjust GDP or provide an alternative. These new measures can help in assessing progress toward sustainability.

Population and Sustainable Development

Population is a key variable in determining potential limits to economic growth, with different implications for developing and currently industrialized countries. For developing countries with rapid population growth rates, it means that limiting population growth is a critical element of sustainable development.

For industrialized countries, the role of population is different. In much of Europe and in Japan, population has stabilized, and for some countries concern has shifted to an emerging pattern of population decline (as we'll see in Chapter 15). In the United States, however, population increase continues to put pressure on both national and global ecosystems. Although the U.S. population growth rate is less dramatic than the rate in many developing regions (0.7 percent per year as opposed to 2–3 percent in many developing countries), the much larger level of U.S. per capita consumption means that each additional U.S. resident creates a much greater additional resource demand than, for example, an additional resident of Nigeria or Bangladesh.

This means that population policy must be an essential element of sustainable development. Population policy must include elements of education, social policy, economic policy, and health care, including availability of contraception, and often runs into conflict with established religious and social mores. Still, this difficult area, generally little considered in standard economic development models, is crucial for sustainability.

Agriculture and Sustainable Development

When we consider agriculture production systems, the general principle of relying as much as possible on renewable resources and natural processes runs counter to much of standard agricultural "modernization." Modern food production relies heavily on inputs such as chemical fertilizers, pesticides, water for irrigation, and mechanization. All of these in turn depend on fossil-fuel energy, and can create environmental and resource problems. Traditional agriculture relies more upon natural fertilizers, solar energy, and animal or human labor.

Agriculture that is compatible with sustainable development can combine elements of modern and traditional techniques. It emphasizes maximum use of renewable resources, such as crop waste and animal manure, as well as crop rotation, intercropping of different plant types, agroforestry, efficient irrigation, minimum-till techniques, and integrated pest management (discussed in Chapter 16). It is still an open question whether this form of agriculture can achieve the yields achieved with input-intensive techniques, but its environmental impacts are less damaging or even beneficial to the environment.

Energy and Sustainable Development

A similar issue arises as to whether renewable energy sources (including wind and solar energy) have the capacity to supplant dependence on fossil fuels. The challenge is a daunting one, because renewables now supply only about 10 percent of energy in industrialized countries. The picture is slightly different in developing countries, where a larger portion of current energy supplies comes from **biomass** (wood, plant, and animal waste). Efficient use of biomass and maintenance of forest resources can thus play an important role in energy policy. Technological advances in solar, wind, and biomass energy systems have brought the prices of these renewable sources down, and their potential for future expansion is significant in both developed and developing countries.

biomass an energy supply from wood, plant, and animal waste.

demand-side management an approach to energy management that stresses increasing energy efficiency and reducing energy consumption.

Huge, often unrecognized, potential lies in conservation and improved efficiency—by some estimates the developed world could reduce its energy use by at least 30 percent through these techniques with little or no effect on living standards. The traditional emphasis on increasing energy supplies could thus give way to a focus on **demand-side management** (increasing efficiency and reducing energy consumption).

Because industrialized countries now account for about half of global energy use (though only 20 percent of global population), increased energy consumption in developing countries could be offset by reductions in developed country energy use. Such reductions could come from increased efficiency rather than requiring reduced living standards. Negotiations over global climate policy (discussed in Chapter 13) suggest that such a tradeoff may be essential to reduce overall human impacts on world climate.

Natural Resources and Sustainable Development

Managing natural resources sustainably implies a combination of economic and ecological perspectives. The economic theory of natural resource management, set forth in Chapters 17–20, shows how many management systems for resources such as forests and fisheries can lead to depletion or even extinction of the resource. Proper incentives and institutions can promote sustainable management. Current management systems for many of the world's fisheries and forests, however, are far from sustainable.

In the area of industrial pollution management, the standard economic approach is to analyze the costs and benefits of various forms of pollution control to determine an economically optimal policy. This approach has its merits, fully considered in Chapter 8, but may be insufficient for sustainability. The best pollution control policy can be overwhelmed by growth in pollution-generating activities, especially those that emit pollutants which accumulate in the environment over time.

Attention has therefore begun to focus on the new concept of industrial ecology as a more comprehensive approach to pollution control. Using the analogy of a natural ecosystem's capacity to recycle its own wastes, this approach attempts to analyze industrial systems as a whole to identify ways in which to minimize or avoid the generation of pollutants and to maximize the recycling of resources. The application of industrial ecology techniques, discussed in Chapter 14, has potential both for restructuring existing industrial systems and for economic development in Latin America, Asia, and Africa.

Tools for Policy Analysis

Replacing the concept of simple economic growth with that of sustainable development offers a new **theoretical paradigm**. Considering a new paradigm of thought is justified because the global reality has changed radically from an earlier period when economic policy could be formulated without much regard to environmental impacts. In this text we will draw on both standard and ecological perspectives to develop aspects of this new paradigm.

theoretical paradigm the basic conceptual approach used to study a particular issue.

The tools of economic analysis, which we study in Part II, are drawn from standard economic theory, while the perspectives presented in Part III respond to the issues of ecological limits on economic growth. The two, in combination, provide a powerful toolbox of analytical techniques with which to address the multifaceted questions of the interrelationship between the environment and the economy.

Summary

Economic growth over time reflects both population and per capita GDP growth. This growth depends on increases in capital stock and technological progress, as well as increased supplies of energy, natural resources, and the capacity of the environment to absorb waste.

Since 1960, unprecedented rates of growth have more than doubled population, more than tripled world agricultural production, and more than quadrupled world GDP and energy use. A review of global environmental trends in five areas—air, land, water, biodiversity, and chemicals and waste—reveals a mix of successes and ongoing challenges. For example, the ozone layer is healing due to the phaseout of CFCs and other chemicals. However, current global climate commitments are insufficient to limit warming to the agreed-upon target of 2 degrees Celsius.

The Limits to Growth model of the relationship between population, industrial output, resources, and pollution indicates that unlimited economic growth will lead to exhaustion of resources, rising pollution, and eventual collapse of economic systems and ecosystems. However, such a model depends on assumptions about technological progress and feedback patterns among the variables in the model. A more optimistic view considers increased efficiency, pollution control, and a transition to alternative, more sustainable technologies.

The concept of sustainable development attempts to combine economic and environmental goals. Sustainable techniques for agricultural production, energy use, natural resource management, and industrial production have significant potential but have yet to be widely adopted. A sustainable global economy also implies limits on population and material consumption. The question of the sustainability of economic activity has already become a major issue and will be even more important in coming decades.

Key Terms and Concepts

absorptive capacity of the environment
biomass
demand-side management
GDP growth rate
gross domestic product (GDP)
Malthusian hypothesis
natural capital
nominal GDP
per capita GDP growth rate
population growth rate
real GDP
"resource curse" hypothesis
theoretical paradigm

Discussion Questions

1. Can we safely say that history has refuted the Malthusian hypothesis? What main factors have worked against Malthus's perspective? Do you identify similarities between the original Malthusian hypothesis and current environmental issues?
2. Over the past several decades, people have worried about the world running out of oil or natural resources. Sufficient oil remains for current needs, however, and no important resources have run short. Have these fears been exaggerated? How would you evaluate them, considering both past experience and future prospects?
3. How do you think we need to approach environmental issues differently in developed and developing countries? What do you see as the main environmental challenges in each?

Notes

1. Data from the Maddison Project, University of Groningen, Groningen Growth and Development Centre, http://www.ggdc.net/maddison/maddison-project/data.htm.
2. Ibid.
3. Based on the Food and Agriculture Organization (FAO) world food price index, which rose from 135 in January 2007 to 220 in March 2008.
4. This relationship is derived from the mathematical rule of natural logarithms stating that if $A = BC$, then $\ln(A) = \ln(B) + \ln(C)$. The rates of growth of B and C can be expressed in terms of natural logarithms, and when added together, they give the rate of growth of A.
5. International Energy Agency, 2014; OECD, 2013.
6. The income categories are determined annually by the World Bank. In 2015 the classifications, based on average per-person income levels, were: high income = greater than \$12,735, middle income = \$1,046 to \$12,735, low income = less than \$1,046.
7. Sachs and Warner, 1995, p. 2.
8. For a study in support of the resource curse hypothesis, see Papyrakis and Gerlagh, 2007. For a study refuting the hypothesis, see Philippot, 2010.
9. UNEP, 2012, p. 32.

10. At the time of writing, preliminary data published by the International Energy Agency indicate that global CO_2 emissions did not increase in 2015 or 2016.
11. World Health Organization, 2010.
12. U.S. Environmental Protection Agency, Lead Air Trends, http://www.epa.gov/air/airtrends/lead.html.
13. World Meteorological Organization and United Nations Environment Programme, 2014.
14. United Nations, International Day for the Preservation of the Ozone Layer web site, http://www.un.org/en/events/ozoneday/background.shtml.
15. UNEP, 2012, p. 66.
16. Sanderson *et al.*, 2002.
17. Crop production index and land data from the World Bank's World Development Indicators database.
18. Neumann *et al.*, 2010.
19. Anonymous, 2014.
20. Shah, 2007.
21. National Groundwater Association, 2015.
22. U.S. EPA, 2011.
23. Frieler *et al.*, 2012.
24. See, for example, Kolbert, 2014.
25. UNEP, 2012, p. 134.
26. Thomas *et al.*, 2004.
27. Urban, 2015.
28. UNEP, 2012, p. 168.
29. UNEP, 2013.
30. OECD, 2008.
31. World Bank, 2012.
32. UNEP, 2009.
33. Caravanos *et al.*, 2011.
34. BBC, 2012.
35. See, for example, Nordhaus, 1992.
36. Turner, 2014.

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Web Sites

1. **www.iisd.org.** The homepage for the International Institute for Sustainable Development, an organization that conducts policy research toward the goal of integrating environmental stewardship and economic development.

2. **www.epa.gov/economics/.** The web site for the National Center for Environmental Economics, a division of the U.S. Environmental Protection Agency that conducts and supervises research on environmental economics. Its web site includes links to many research reports.

3. **http://ase.tufts.edu/gdae/.** The homepage for the Global Development and Environment Institute at Tufts University, "dedicated to promoting a new understanding of how societies can pursue their economic goals in an environmentally and socially sustainable manner." The site includes links to many research publications.

4. **www.wri.org.** The World Resources Institute web site offers the biennial publication *World Resources* as well as extensive reports and data on global resource and environmental issues.

PART

II

Economic Analysis of Environmental Issues

CHAPTER 3

The Theory of Environmental Externalities

Chapter 3 Focus Questions

- How can pollution and environmental damage be represented in economics?
- What economic policies can be instituted to respond to environmental problems?
- How and when can property rights be relied upon to solve environmental problems?

3.1 THE THEORY OF EXTERNALITIES

We saw in Chapter 1 that one of the core concepts of environmental economics is the theory of environmental externalities. Externalities were defined as impacts that affect the well-being of those outside of a market transaction. Externalities can be either positive or negative. The most common example of a **negative externality** is pollution. If markets operate without any regulation, the production decisions of companies will not account for the social and ecological damages of pollution. Consumers also typically will not limit their purchases because of pollution caused by the goods and services that they purchase. But it is important that economic analysis considers not just the ways markets impact buyers and sellers, but how markets affect all members of society. (It may also be relevant to consider impacts on non-human species and on ecosystems in general—this issue will be dealt later in this chapter and also in Chapters 6 and 7). So when we analyze the overall impacts of a market, we need to account for the damages from pollution.

negative externality negative impacts of a market transaction affecting those not involved in the transaction.

In some cases, a market transaction can generate a **positive externality** if it benefits those external to the market. An example of a positive externality is a landowner who buys and plants trees. In addition to benefits to the owner, the trees provide benefits to those who appreciate the scenery and to society as a whole because they absorb carbon dioxide and provide habitat for wildlife.

In a basic economic analysis of markets, demand and supply curves represent the costs and benefits of a transaction. A supply curve tells us the **marginal cost** of production—in other words, the costs of producing one more unit of a good or service. Meanwhile, a demand curve can also be considered a **marginal benefit** curve because it tells us the perceived benefits consumers obtain from consuming one additional unit. The intersection point of a demand and supply curve gives the **equilibrium price** at which supply and demand balance, as shown in Figure 3.1 for a hypothetical market for automobiles. This equilibrium (at a price of P_M and a quantity of Q_M) represents a situation of **economic efficiency** because it maximizes the total benefits from the market—but only if there are no externalities. (See Appendix 3.1 for an overview of supply, demand, equilibrium, and efficiency in markets.)

positive externality the positive impacts of a market transaction that affect those not involved in the transaction.

marginal cost the cost of producing or consuming one more unit of a good or service.

marginal benefit the benefit of producing or consuming one more unit of a good or service.

equilibrium price the market price where the quantity supplied equals the quantity demanded.

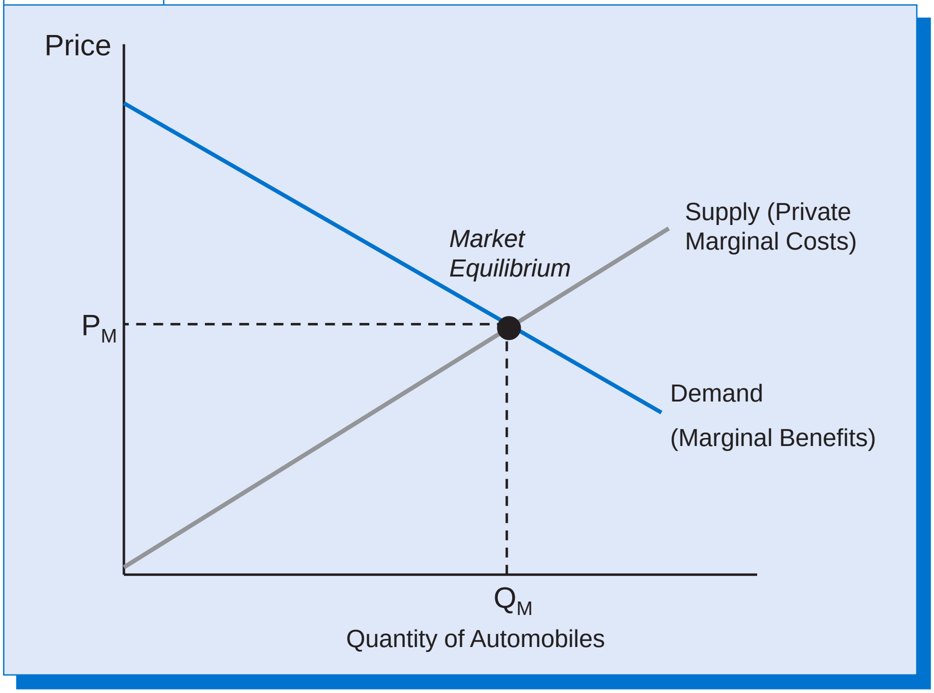
economic efficiency an allocation of resources that maximizes net social benefits; perfectly competitive markets in the absence of externalities are efficient.

Accounting for Environmental Costs

But this market equilibrium does not tell the whole story. The production and use of automobiles create numerous negative externalities. Automobiles are a major contributor to air pollution, including both local urban smog and regional problems such as acid rain. In addition, their emissions of carbon dioxide contribute to global warming. Automobile oil leaked from vehicles or disposed of improperly can pollute lakes, rivers, and groundwater. The production of automobiles involves the use of toxic materials that can be released to the environment as toxic wastes. The road system required for automobiles paves over many acres of wildlife habitat, and salt runoff from roads damages watersheds.

Where do these various costs appear in Figure 3.1? The answer is that they do not appear at all. Thus the market overestimates the net social benefits of automobiles because the costs

Figure 3.1 The Market for Automobiles



Note: Private marginal costs are the costs of production to private producers.

> **internalizing external costs/externalities** using approaches such as taxation to incorporate external costs into market decisions.
>
> **external cost(s)** a cost, not necessarily monetary, that is not reflected in a market transaction.

of the negative externalities are not considered. So we need to find ways of **internalizing externalities**—bringing the **external costs** into our market analysis.

The first problem in doing this is assigning a monetary value to environmental damages. How can we reduce the numerous environmental effects we have identified to a single monetary value? There is no clear-cut answer to this question. In some cases, economic damages are identifiable. For example, if road runoff pollutes a town's water supply, the cost of water treatment gives at least one estimate of environmental damages. However, this does not include less tangible factors such as damage to lake and river ecosystems.

If we can identify the health effects of air pollution, the resulting medical expenses will give us another monetary damage estimate, but this does not capture the aesthetic damage done by air pollution. Smoggy air limits visibility, which reduces people's well-being even if it does not have a measurable effect on their health. Issues such as these are difficult to compress into a monetary estimate. Yet if we do not assign a monetary value to environmental damages, the market implicitly assigns a value of zero, because none of these issues are directly reflected in consumer and producer decisions about automobiles. We will discuss the techniques economists use to value environmental impacts in more detail in Chapter 6.

Some economists have attempted to estimate the external costs of automobiles in monetary terms (see Box 3.1 and Table 3.1). Assuming we have a reasonable estimate of these external costs, how can these be added to our supply and demand analysis in Figure 3.1?

Box 3.1
THE EXTERNAL COSTS OF AUTOMOBILE USE

What are the external, or social, costs of motor vehicle use? Automobiles are considered to be the largest source of several major air pollutants including carbon monoxide and nitrogen oxides. According to the U.S. EPA, transportation accounts for about 13 percent of global greenhouse gas emissions.[1] The World Health Organization estimates that over one million deaths occur each year due to accidents on the world's roads.[2] Additional external costs include the destruction of natural habitats from building roads and parking lots, the disposal of vehicles and parts, military costs associated with securing petroleum supplies, and noise pollution.

Attempts to estimate the external costs of automobiles focus on developed countries. A 2007 article summarized the existing literature on automobile externalities in the United States[3] and presented a "best assessment" of automobile externalities per mile, divided into several categories as shown in Table 3.1. Converted to damages per gallon of gasoline, the damages are $2.10 per gallon.

These estimates suggest that externalities from automobile use in the United States amount to about 3 percent of GDP.

A similar study was conducted in Europe in 2012.[4] The results of this study are also presented in terms of externality damages per mile in Table 3.1. Note that the final estimate, 9 cents per mile, is quite similar to the U.S. estimate. The European study estimates higher climate change damages but omits an estimate of congestion damages (which is close to half of total U.S. damages). The climate change estimate used in the U.S. is equivalent to a damage of $20 per ton of carbon emitted. We'll see in Chapter 13 that other estimates of climate damages are significantly higher.

A tax on gasoline is one way to internalize the external costs of automobile use, but as noted in the U.S., using a range of policy approaches is a more effective way to fully internalize all the costs associated with automobile use. For example, internalizing air pollution externalities should ideally be based on a vehicle's emissions level rather than gasoline consumption. The externalities associated with congestion could be internalized through congestion tolls that charge drivers on busy roads depending on the time of the day, using electronic sensors.

Table 3.1 External Costs of Automobile Use, U.S. Cents per Mile, United States and Europe

Cost Category	United States Estimate	Europe Estimate
Climate Change	0.3	3.3
Local Pollution (air and noise)	2.0	0.8
Accidents	3.0	3.7
Oil Dependency	0.6	Not estimated
Traffic Congestion	5.0	Not estimated
Other External Costs	Not estimated	1.2
Total	10.9	9.0

Sources: Parry *et al.*, 2007; Becker *et al.*, 2012.

Note: Original European estimates were in euros per kilometer. Conversion to cents per mile based on 2016 currency conversion rates.

social marginal cost curve the cost of providing one more unit of a good or service, considering both private production costs and externalities.

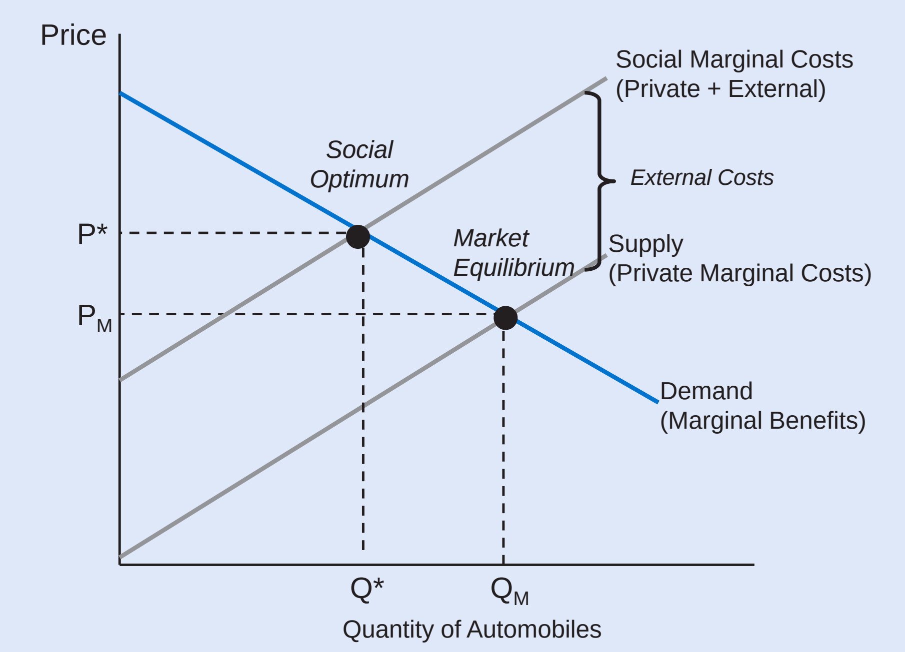
Recall that a supply curve tells us the marginal costs of producing a good or service. But in addition to the normal private production costs, such as the labor, steel, and electricity to produce a car, we now also need to consider the environmental costs—the costs of the negative externalities. So we can add the external costs to the production costs to obtain the total social costs of automobiles. This results in a new cost curve, which we call a **social marginal cost curve**. This is shown in Figure 3.2.

The social marginal cost curve is above the original market supply curve because it now includes the external costs. Note that the vertical distance between the two cost curves is our estimate of the external costs of each automobile, measured in dollars. In this simple case, we have assumed that the external costs of automobiles are constant. Thus the two curves are parallel. This is probably not the case in reality, as the external costs of automobiles can change depending on the number of automobiles produced. Specifically, the external costs of an additional automobile are likely to increase when more automobiles are produced as air pollution exceeds critical levels and congestion becomes more severe.

Considering Figure 3.2, is our market equilibrium still the economically efficient outcome? It is definitely not. To understand why, you can think of the decision to produce each automobile as depending on a comparison of the marginal costs to the marginal benefits. If the marginal benefit exceeds the marginal cost at a particular level of automobile production, considering all benefits and costs, then from the social perspective it makes sense to produce that automobile. But if the cost exceeds the benefit, then it does not make sense to produce that particular automobile.

So, in Figure 3.2 we see that it makes sense to produce the first automobile because the demand curve (reflecting the marginal benefits) is above the social marginal cost curve (reflecting the sum of the production and external costs). Even though the first automobile creates some negative externalities, the high marginal benefits justify producing that automobile. We

Figure 3.2 The Market for Automobiles with Negative Externalities



see that this is true for each automobile produced up to a quantity of Q^*. At this point, the marginal benefits equal the social marginal costs. But then notice that for each automobile produced beyond Q^*, the marginal social costs are actually above the marginal benefits. In other words, for each automobile produced above Q^*, society is becoming worse off!

So, our unregulated market outcome, at Q_M, results in a level of automobile production that is too high. We should produce automobiles only as long as the marginal benefits are greater than the marginal social costs. Thus the optimal level of automobile production is Q^*, not the market outcome of Q_M. Rather than producing the maximum benefits for society, the equilibrium outcome is inefficient in the presence of a negative externality. We can also see in Figure 3.2 that from the perspective of society, the market price of automobiles is too low—that is, it fails to reflect the true social costs of automobiles, including the environmental impacts. The **socially efficient** price for automobiles is higher, at P^*. (See Appendix 3.2 for a more formal analysis of negative externalities.)

socially efficient a market situation in which net social benefits are maximized.

Internalizing Environmental Costs

What can we do to correct this inefficient market equilibrium? The solution to our problem lies in getting the price of automobiles "right." The market fails to send a signal to consumers or producers that further production past Q* is socially undesirable. While each automobile imposes a cost upon society, neither the consumers nor the producers pay this cost. So, we need to "internalize" the externality so that these costs now enter into the market decisions of consumers and producers.

The most common way to internalize a negative externality is to impose a tax. This approach is known as a **Pigovian tax**, after Arthur Pigou, a well-known British economist who published his *Economics of Welfare* in 1920. It is also known as the **polluter pays principle**, since those responsible for pollution pay for the damages they impose upon society.

Pigovian (pollution) tax a per-unit tax set equal to the external damage caused by an activity, such as a tax per ton of pollution emitted equal to the external damage of a ton of pollution.

polluter pays principle the view that those responsible for pollution should pay for the associated external costs, such as health costs and damage to wildlife habitats.

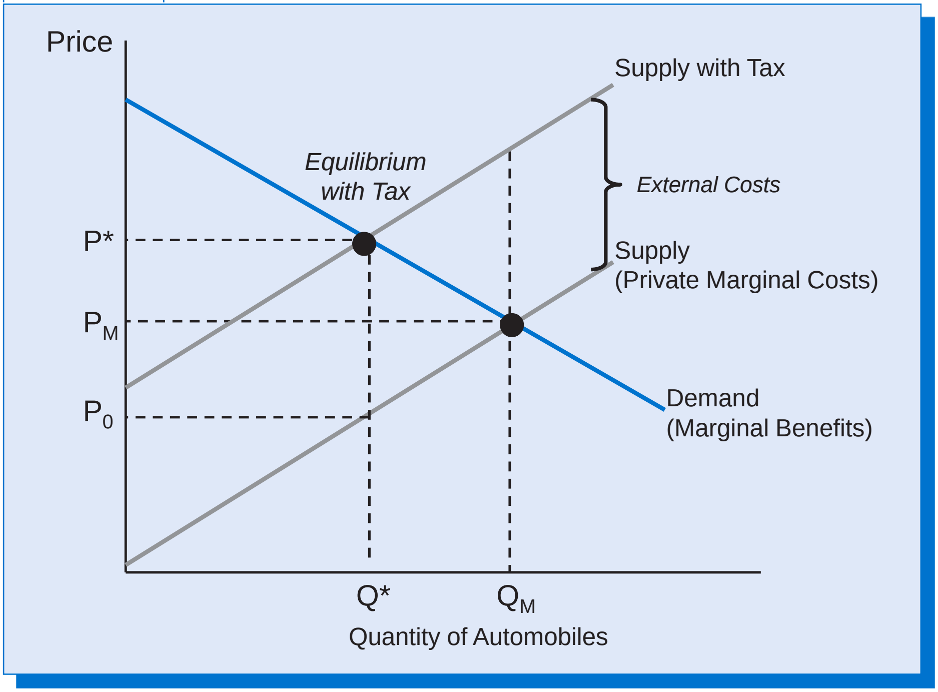
For simplicity, assume that the tax is paid by automobile manufacturers.[5] For each automobile produced, they must pay a set tax to the government. But what is the proper tax amount?

By forcing manufacturers to pay a tax for each automobile produced, we have essentially increased their marginal production costs. So, you can think of a tax as shifting the private marginal cost curve upward. The higher the tax, the more we would shift the cost curve upward. So, if we set the Pigovian tax exactly equal to the externality damage associated with each automobile, then the marginal cost of production would equal the social marginal cost curve in Figure 3.2. This is the "correct" tax amount—the tax per unit should equal the externality damage per unit.[6] In other words, those responsible for pollution should pay for the full social costs of their actions.

In Figure 3.3, the new supply curve with the tax is the same curve as the social marginal cost curve from Figure 3.2. It is the operative supply curve when producers decide how many automobiles to supply, because they now have to pay the tax in addition to their manufacturing costs.

The market will adjust to the Pigovian tax by shifting to a new equilibrium, with a higher price of P^* and a lower quantity of Q^*. The tax has resulted in the optimal level of automobile production. In other words, automobiles are produced only to the point where the marginal benefits are equal to the social marginal costs. Also note that even though the tax was levied on producers, a portion of the tax is passed on to consumers in the form of a price increase for automobiles (from P_M to P^*). This causes consumers to cut back their purchases from Q_M to Q^*.

Figure 3.3 Automobile Market with Pigovian Tax



From the point of view of achieving the socially optimal equilibrium, this is a good result. Of course, neither producers nor consumers will like the tax, since consumers will pay a higher price and producers will have lower sales, but from a social point of view we can say that this new equilibrium is optimal because it accurately reflects the true social costs of automobiles.

Our story tells a convincing argument in favor of government regulation in the presence of negative externalities. The tax is an effective policy tool for reaching a more efficient outcome for society. But should the government always impose a tax to counter a negative externality? The production of virtually all good or services results in some pollution damages. So, it may seem as if the government should tax the vast majority of products on the basis of their environmental damage.

But two factors suggest we probably should not put a Pigovian tax on all products. First, recall that we need to estimate the tax amount in monetary terms, which requires economic research and analysis, perhaps along with toxicological and ecological studies. Some products cause relatively minimal environmental damages, and the small amount of taxes collected may not be worth the costs of estimating the "right" tax. Second, we need to consider the administrative costs of imposing and collecting the tax. Again, if a product does not cause much environmental damage, then these costs might outweigh the revenues we would collect.

Determining the appropriate tax on every individual product that causes environmental damage would be a monumental task. For example, we might impose a tax on shirts because the production process could involve growing cotton, using petroleum-based synthetics, applying potentially toxic dyes, and so on. But we would ideally need to set a different tax on shirts made with organic cotton, or those using recycled plastics, or even shirts of different sizes!

upstream tax a tax implemented as near as possible to the point of natural resource extraction.

Rather than looking at the final consumer product, economists generally recommend applying Pigovian taxes as far upstream in the production process as possible. An **upstream tax** is imposed at the level of the raw production inputs, such as the crude oil or cotton used to make a shirt. If we determine the appropriate Pigovian tax on cotton, then this cost will be reflected in the final selling price of the shirt based on how much cotton is used in production. We could focus our taxation efforts on those raw materials that cause the most widespread ecological damage. So, we might tax fossil fuels, various mineral inputs, and toxic chemicals. This limits the administrative complexity of tax collection and avoids the need for estimating the appropriate tax for a multitude of products.

The policy implications for a system of externality taxes on the extraction and processing of raw materials are significant. As discussed in Box 3.2, a 2013 study[7] estimated the global externalities generated from "primary" production industries (including agriculture, fishing, mining, power generation, and initial materials processing) to be $7.3 trillion, or 13 percent of world economic production. For comparison, the World Bank estimates current global tax revenues to be approximately 14 percent of world economic production.[8] Thus implementing a complete global system of Pigovian taxes would have dramatic implications for the world economy.

Box 3.2

ESTIMATING GLOBAL ENVIRONMENTAL EXTERNALITIES

While many studies have estimated externality damages for specific environmental impacts and in specific locations, few estimates are available regarding the global extent of externalities. A 2013 study by Trucost, an environmental consulting company, is perhaps the most comprehensive attempt to monetize global environmental externalities.[9] The research finds that in 2009 primary production and processing industries generated $7.3 trillion in unpriced externality damages, equivalent to 13 percent of world economic output. The breakdown of these damages is given in Table 3.2.

Among the most significant impacts are the damages from coal power generation in Eastern Asia and North America, cattle ranching and farming in South America, and wheat and rice farming in Southern Asia. An interesting component of the research is that it compares the externality damages generated by specific industries to total revenues. In many cases the externalities far exceed industry revenues, suggesting that these markets are highly inefficient. For example, coal power generation in North America causes $317 billion in environmental damages but generates only $247 billion in revenues. Rice farming in Northern Africa produces about $2 billion in revenues yet results in $84 billion in damages.

An earlier 2011 version of the research found that the world's largest 3,000 companies cause one-third of global environmental damages.[10] Further, these damages equate to 50 percent of these companies' combined earnings. The 2011 study also projects global externalities into the future under a business-as-usual scenario. It estimates that in 2050 global external costs will rise to 18 percent of world economic production, with over 70 percent of these damages due to greenhouse gas emissions. The study notes that the "failure to maintain natural capital, if uncorrected, will undermine economic growth over time."

Table 3.2 Global Environmental Externalities

Impact Category	Damages
Land use	$1.8 trillion
Water consumption	$1.9 trillion
Greenhouse gases	$2.7 trillion
Air pollution	$0.5 trillion
Land and water pollution	$0.3 trillion
Waste generation	$0.05 trillion

Source: Trucost, 2013.

Another issue related to our externality analysis is to explore how the tax burden is distributed between producers and consumers. Many noneconomists claim that any taxes are simply passed on to consumers in terms of higher prices. While it is true that the automobile tax raised prices, was the full cost passed on to consumers? The answer is no. Note that the tax per unit was the vertical difference between P_0 and $P*$ in Figure 3.3. But the price went up only by the difference between P_M and $P*$ (a smaller vertical distance in the graph). In this example, it seems that the tax burden was borne about equally by consumers and producers.

elasticity of supply the sensitivity of quantity supplied to prices; an elastic supply means that a proportional increase in prices results in a larger proportional change in quantity supplied; an inelastic supply means that a proportional increase in prices results in a small change.

elasticity of demand the sensitivity of quantity demanded to prices; an elastic demand means that a proportional increase in prices results in a larger proportional change in quantity demanded; an inelastic demand means that a proportional increase in prices results in a small change.

In some cases, the tax burden may fall more heavily on producers, while in other cases the burden may fall mostly on consumers. It depends on the **elasticities of supply and demand** with respect to price—how responsive supply and demand are to price changes. We discuss the topic of elasticities in more detail later in the text, including Appendix 3.1.

A final consideration is that a tax can fall disproportionately on certain income groups. One concern with most environmental taxes, such as taxes on fossil fuels, is that they hit low-income households the hardest. This is because the lower a household's income is, the more they tend to spend, as a share of their income, on fossil-fuel products, including gasoline and electricity. So we might wish to use some of the tax revenues to counteract the impact on low-income households, perhaps in the form of tax credits or rebates.

In practice, environmental policy often takes the form of other kinds of regulation besides taxes, such as, in the case of automobiles, fuel efficiency standards or mandated pollution control devices such as catalytic converters. These policies reduce fuel consumption and pollution without necessarily reducing the number of automobiles sold. They are also likely to drive up the purchase price of automobiles, so in this respect their effects are somewhat similar to a tax (although greater fuel efficiency reduces operating costs). We'll compare different pollution control policies in more detail in Chapter 8.

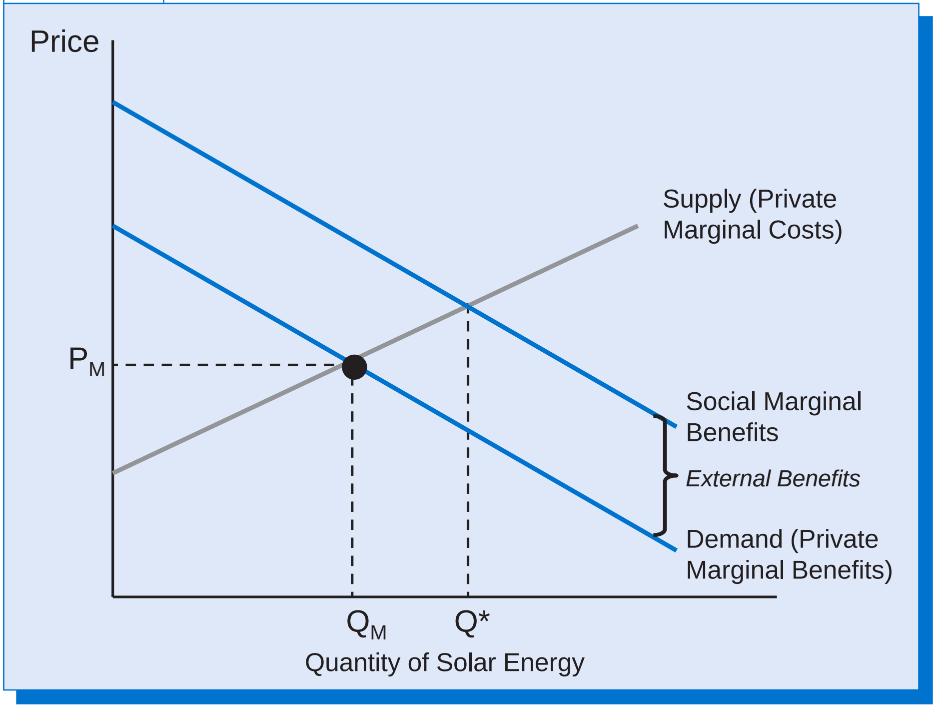
Positive Externalities

Just as it is in society's interest to internalize the social costs of pollution, it is also socially beneficial to internalize the social benefits of activities that generate positive externalities. As with a negative externality, an unregulated market will also fail to maximize social welfare in the presence of a positive externality. Similarly, a policy intervention will be required to reach the efficient outcome.

A positive externality is an additional social benefit from a good or service beyond the private, or market, benefits. Because a demand curve tells us the private marginal benefits of a good or service, we can incorporate a positive externality into our analysis as an upward shift of the demand curve. This new curve represents the total social benefits of each unit.

Figure 3.4 shows the case of a good that generates a positive externality—solar panels. Each solar panel installed reduces emissions of carbon dioxide and other pollutants, and thus benefits society as a whole. The vertical distance between the market demand curve and the social marginal benefits curve is the positive externality per solar panel, measured in dollars. In this example, the social benefits are constant per panel, so the two benefit curves are parallel.

Figure 3.4 The Market for Solar Energy with Positive Externalities



The market equilibrium price is P_M, and quantity is Q_M. But notice in Figure 3.4 that between Q_M and Q^*, marginal social benefits exceed the marginal costs. Thus the optimal level of solar energy is Q^*, not Q_M. So we can increase net social benefits by increasing the production of solar energy.

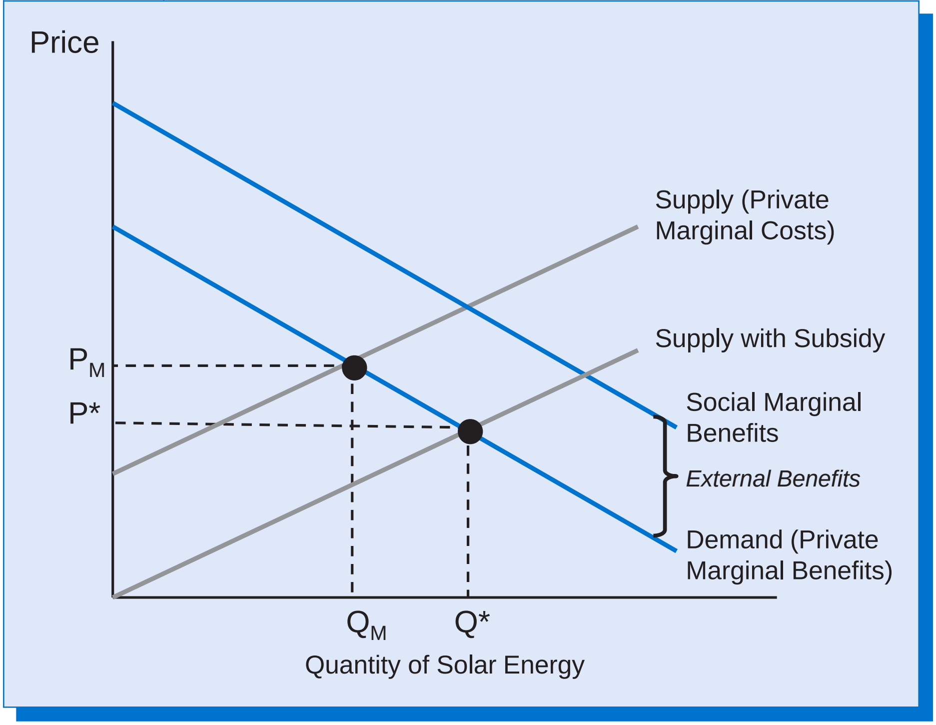
In the case of a positive externality, the most common policy to correct the market inefficiency is a subsidy. A **subsidy** is a payment to a producer to provide an incentive for it to produce more of a good or service. In some cases, subsidies are instead paid to consumers to encourage them to purchase particular goods and services.

> **subsidy** government assistance to an industry or economic activity; subsidies can be direct, through financial assistance, or indirect, through other beneficial policies.

The way to illustrate a subsidy in our market analysis is to realize that a subsidy to providers effectively lowers the cost of producing something. So, a subsidy lowers the supply curve by the amount of the per-unit subsidy. In essence, a subsidy makes it cheaper to produce solar panels, because for every panel produced the manufacturer gets a payment from the government. The "correct" subsidy lowers the supply curve such that the new market equilibrium will be at Q^*, which is the socially efficient level of production. This is illustrated in Figure 3.5, with equilibrium at the point where the supply curve with the subsidy intersects the market demand curve. The principle parallels the use of a tax to discourage economic activities that create negative externalities—except that in this case we want to encourage activities that have socially beneficial side effects. (See Appendix 3.2 for a more detailed analysis of positive externalities.)

The socially efficient equilibrium quantity Q^* could also be achieved with a subsidy to consumers for buying solar panels, such as a tax credit. This would have the effect of shifting the demand curve up and to the right, leading to a higher market price but a lower effective price to consumers due to the subsidy, and the same equilibrium quantity as with a producer subsidy.

Figure 3.5 The Market for Solar Energy with a Subsidy



3.2 WELFARE ANALYSIS OF EXTERNALITIES

We can use a form of economic theory called **welfare analysis** to show in more detail why it is socially preferable to internalize externalities. The idea here is that *areas* on a supply and demand graph can be used to measure total benefits and costs. The area under the market demand curve shows the total benefit to consumers; the area under the market supply curve shows the total cost to producers. For each unit purchased, the demand curve shows the value of that unit to consumers.

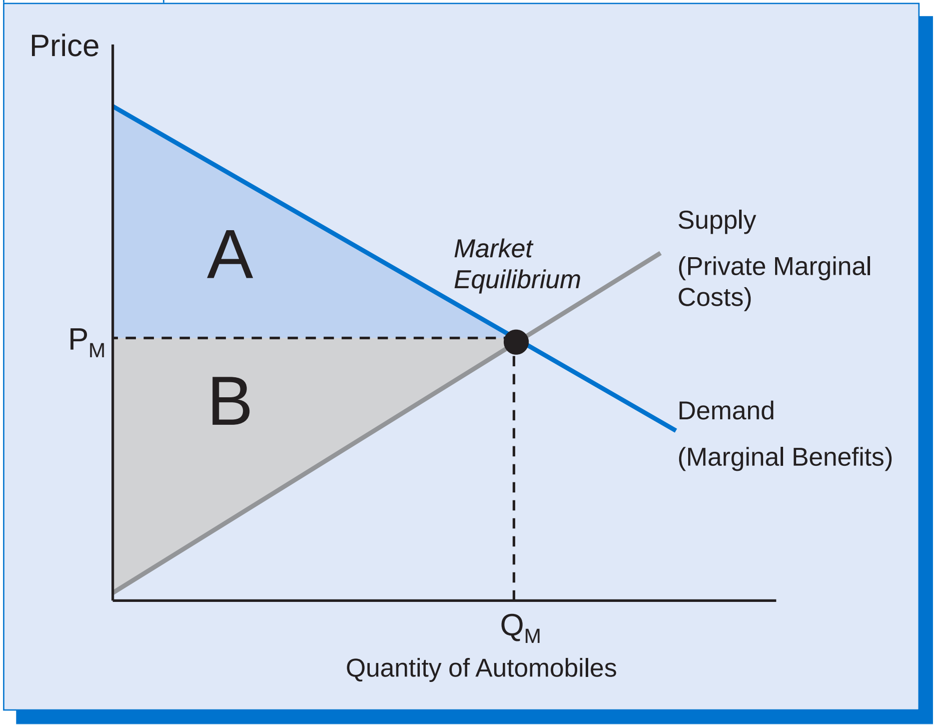
welfare analysis an economic tool that analyzes the total costs and benefits of alternative policies to different groups, such as producers and consumers.

This concept is illustrated in Figure 3.6, which presents a welfare analysis of the automobile market. Because the supply and demand curves, as noted above, show the *marginal* benefits and costs for each individual unit produced, the areas under these curves in effect sum up the *total* benefits and costs for all units produced. For consumers, total net benefits are called consumer surplus (area A)—representing the difference between their benefits from the consumption of automobiles, as shown by the demand curve, and the price they pay, as shown by the horizontal line at P_M. Producers gain a net benefit defined as producer surplus (area B)—the difference between their production costs, shown by the supply curve, and the price P_M that they receive. (Appendix 3.1 provides a background overview of market analysis, including a discussion of consumer and producer surplus.)

In the absence of externalities, the market equilibrium is economically efficient because it maximizes the net social benefit (areas A + B). But if we introduce externalities, the market equilibrium is no longer economically efficient.

We can define the net social benefits of the automobile market as the sum of consumer and producer surplus minus the externality damage. Thus net benefits equal the market

Figure 3.6 Welfare Analysis of the Automobile Market



benefits (areas A and B in Figure 3.6) minus negative externality damages. This is shown in Figure 3.7. Here we superimpose externality damages, shown by the area between the private marginal cost curve and the social marginal cost curve, on Figure 3.6. (Figure 3.7 is equivalent to Figure 3.2, showing negative externalities in exactly the way we did earlier, but it also shows the total external costs, equal to the dark gray area).

Note that the externality damages effectively offset parts of consumer and producer surplus. Net social welfare in the presence of the negative externality is (A' + B' – C), where C is just the triangular area to the right of *Q** marked by dashed lines. We have used the notation of A' and B' because these areas are smaller than areas A and B from Figure 3.6. A' and B' represent the areas of consumer and producer surplus that are not offset by subtracting the externality damage. But note that actual consumer and producer surplus are not lowered by the presence of the negative externality. Consumer surplus remains area A from Figure 3.6, and producer surplus remains area B. But parts of the benefits of A and B are offset by the social loss from pollution. In addition to these smaller areas of net benefits, area C represents a loss, because between *Q** and Q_M social marginal costs exceed marginal benefits (the demand curve).

Now consider the imposition of a Pigovian tax to internalize the externality. The tax will shift the equilibrium from Q_M to *Q**. We can prove that net social welfare has increased as a result of the tax by comparing the net welfare before the tax, area (A' + B' – C) from Figure 3.7, to net welfare in Figure 3.8. With price at *P** and quantity at *Q**, our new consumer surplus is A" and producer surplus is B". Note that the sum of A" and B" is the same as the sum of A' and B' from Figure 3.7—as we will see shortly, this point is critical to our analysis.

As we are only producing *Q** automobiles instead of Q_M, the externality damages are now area D, which is less than the externality damages from Figure 3.7. The per-unit tax is the vertical distance between the two supply curves. This tax is collected on a quantity of *Q** automobiles. Thus the total tax revenue is represented by area D. The tax revenue exactly

Figure 3.7 Welfare Analysis of the Automobile Market with Externalities

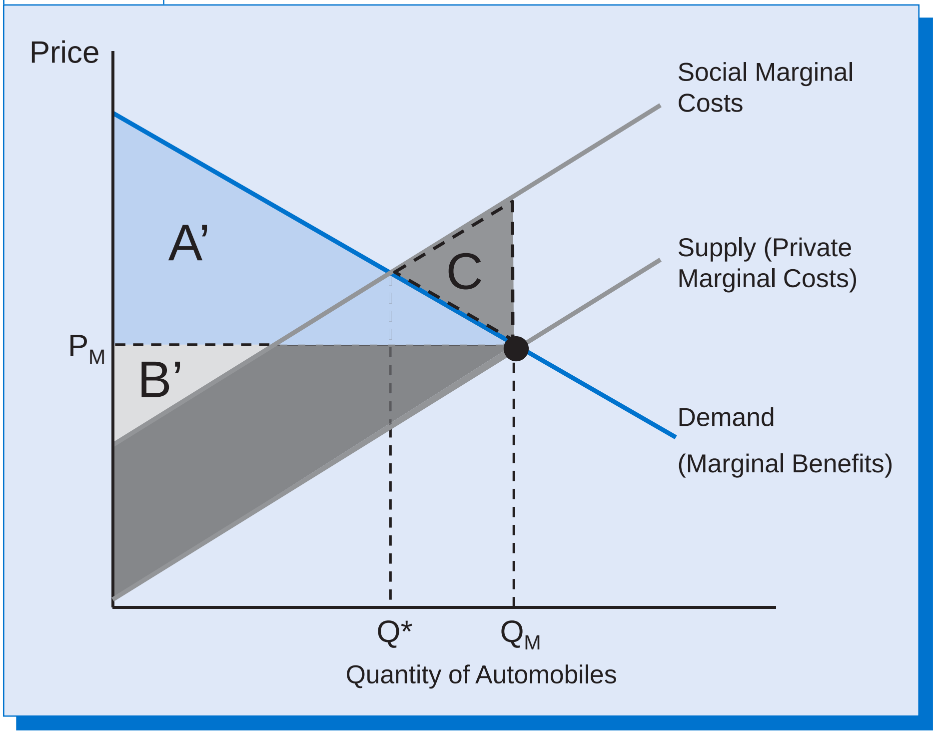
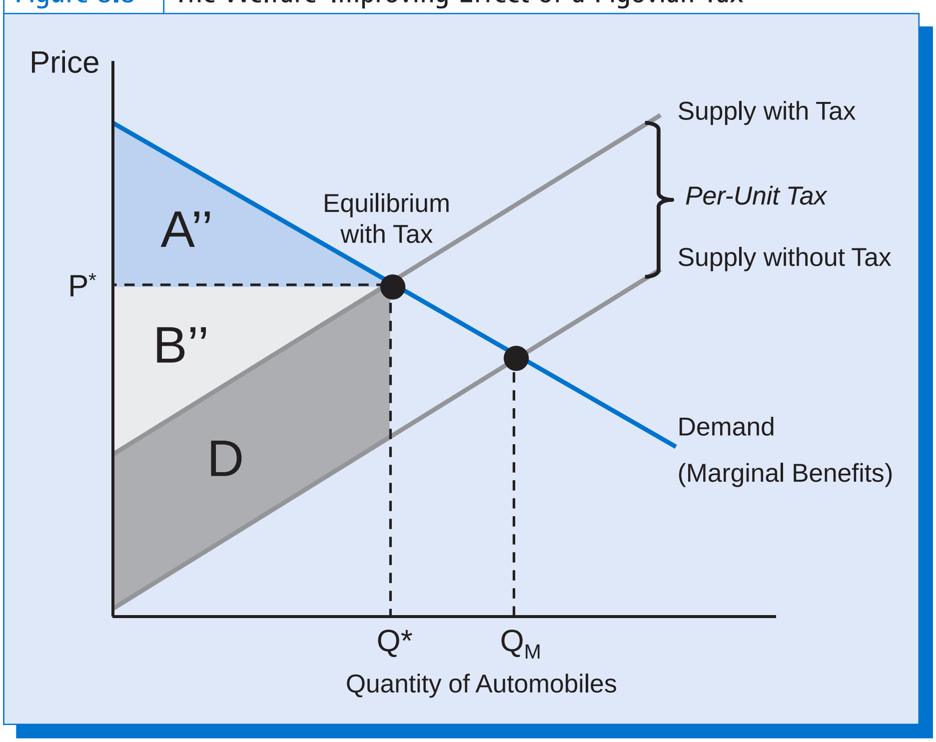


Figure 3.8 The Welfare-Improving Effect of a Pigovian Tax



equals the externality damages. In other words, the tax revenue is exactly sufficient to fully compensate society for the externality damages.

The net social welfare is the sum of consumer and producer surplus, minus the externality damages, plus the benefit of the tax revenue, or:

$$\begin{aligned} \textit{Net Social Welfare} &= A'' + B'' - D + D \\ &= A'' + B'' \end{aligned}$$

As we mentioned above, area (A'' + B'') equals area (A' + B'). Recall that net social welfare before the tax was (A' + B' – C). Now net social welfare is effectively (A' + B'). Net social welfare has increased as a result of the Pigovian tax by area C. Society is better off with the tax than without it!

A similar welfare analysis of a positive externality and the impacts of a subsidy can be used to show that a subsidy in the presence of a positive externality increases net social welfare. The analysis is a bit more complex and is presented in Appendix 3.2.

Optimal Pollution

Our analysis of negative externalities reveals an idea that may seem paradoxical—the concept of **optimal pollution**. Note that even after imposing an externality tax, society is still left with pollution damages of area D in Figure 3.8. According to our analysis, this is the "optimal" amount of pollution based on current production costs and technologies. But you might object—Isn't the optimal level of pollution *zero*?

optimal level of pollution the pollution level that maximizes net social benefits.

The economist's answer would be that the only way to achieve zero pollution is to have zero production. If we want to produce virtually any manufactured good, some pollution will result. We as a society must decide what level of pollution we are willing to accept. Of course, we can strive to reduce this level over time, especially through pollution-reducing technology, but as long as we have production we will have to determine an "optimal" pollution level.

Some people remain uneasy with the concept of optimal pollution. Note, for example, that if the demand for automobiles increases, the demand curve will shift to the right and the "optimal" pollution level will increase. This suggests that as global demand for automobiles rises steadily, ever-rising levels of pollution will, in some sense, be acceptable. We might choose instead to set a maximum level of acceptable pollution based on health and ecological considerations, rather than economic analysis. In fact, the main federal air pollution law in the United States, the Clean Air Act, sets pollution standards based on scientific data on health impacts, explicitly ruling out economic considerations in setting standards.

The question of overall limits on pollution levels can be related to the notion of economic scale that we discussed in Chapter 1. Ecological economists would tend to favor reliance upon something other than economics to determine the overall scale of allowable negative externalities, even if Pigovian taxes are used to control externalities at the individual market level. We discuss pollution policies and the concepts of optimal pollution, overall limits on pollution, and policies to "green" the economy, in more detail in Chapters 8 and 14.

3.3 PROPERTY RIGHTS AND THE ENVIRONMENT

The idea of a Pigovian tax, which forces polluters to pay for the cost of their social and environmental damages, is intuitively appealing. Implicit in the imposition of a Pigovian tax is the idea that society has a legitimate right to be compensated for any pollution damages. Many people would contend that this is an appropriate allocation of rights. In other words, society has a right to clean air, but polluters do not have a right to emit whatever they want into the atmosphere.

In other cases, the appropriate allocation of rights may be less clear cut. Suppose a farmer drains a wetland on his property to create a field suitable for growing crops. His downstream neighbor complains that without the wetland to absorb heavy rainfall, her land now floods, damaging her crops. Should the first farmer be obliged to pay the second the value of any crop damages? Or does he have the right to do what he wants on his own land?

We can see that this is an issue not just of externalities but also of the nature of property rights. Does the ownership of land include a right to drain wetlands on that land? Or is this right separate, subject to control by the community or other property owners?

The property rights in this case could be allocated in one of two ways. Suppose we say that the first farmer (call him Albert) *does* have the right to drain the wetland on his land. Assume that the net value of crops grown on this drained wetland is $5,000. Further, let's suppose that the second farmer (call her Betty) would suffer crop losses of $8,000 if the land were drained. We also assume that both Albert and Betty have accurate information regarding their potential costs and benefits. Even though Albert has the right to drain the wetland, Betty could potentially pay Albert not to drain it. Specifically, she would be willing to pay Albert up to $8,000 to keep the wetland intact, because that is the value of the damage she would suffer if Albert exercises his right to drain it. Meanwhile, Albert would be willing to accept any amount higher than $5,000, because that is what he stands to gain by draining the wetland.

Between $5,000 and $8,000 lies sufficient negotiation space for Albert and Betty to reach an agreement that satisfies both of them. Let's say that Albert accepts an offer of $6,000 from Betty to keep the wetland intact. He gains $1,000 relative to what he would have made by draining the wetland. Betty is not happy about paying $6,000, but she is better off than she would be if the wetland was drained and she lost $8,000. In effect, Betty purchases the right to say how the wetland will be used (without having to purchase the land).

Society can also assign the relevant right to Betty, by passing a law stating that no one can drain a wetland without the agreement of any affected parties downstream. In that case, Albert would have to reach an agreement with Betty before he could drain the wetland. With the crop values that we have assumed, the same result will be reached—the wetland will not be drained, because the value of doing so to Albert ($5,000) is not enough to compensate Betty for her loss. Betty will demand at least $8,000 to grant her permission, and this price is too high for Albert. So, regardless of who holds the property rights, the same outcome is achieved—the wetland is not drained.

Now suppose that a new gourmet crop item becomes popular, a crop that grows well on former swampland and would bring Albert $12,000 in profit. A deal is now possible—Albert can pay Betty, say, $10,000 for the right to drain the swamp and earn $12,000 from the new crop, netting $2,000 profit for himself and leaving Betty $2,000 better off as well.

Note that Albert could offer Betty an amount lower than $10,000. In theory, Betty would accept any payment greater than $8,000. But Albert would be willing to pay up to $12,000 for the right to drain the swamp. The actual price Albert would pay depends on the bargaining abilities of the two parties.

The principle at issue in this simple example has come to be known as the **Coase theorem**, after Ronald Coase, a Nobel prize–winning economist who discussed similar examples of property rights and externalities in his 1960 article "The Problem of Social Cost."[11] The Coase theorem states that if property rights are well defined, and there are no **transaction costs**, an efficient

Coase theorem the proposition that if property rights are well defined and there are no transactions costs, an efficient allocation of resources will result even if externalities exist.

transaction costs costs associated with a market transaction or negotiation, such as legal and administrative costs to transfer property or to bring disputing parties together.

allocation of resources will result even if there are externalities. Transaction costs are costs involved in reaching and implementing an agreement, which can include costs of obtaining information (such as surveying the land), time and effort spent in negotiations, and costs of enforcing the agreement. In the case of Albert and Betty, these costs should be low, because they need only to reach an understanding about the amount of compensation, although legal costs may be involved in formalizing an agreement.

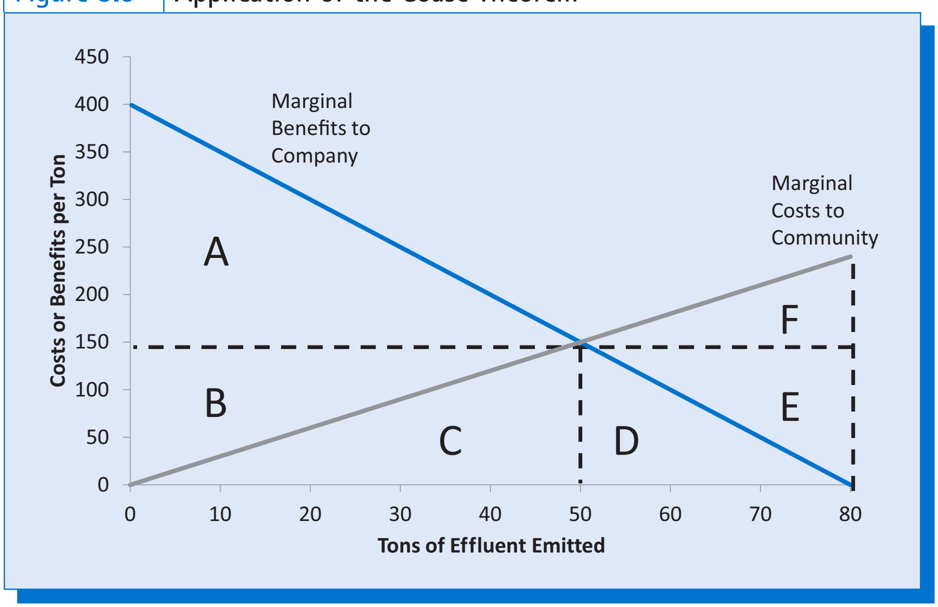
Through negotiations, the two parties will balance the external costs against the economic benefits of a given action (in this case, draining the wetland). In the example above, the external costs were \$8,000. It is not worth incurring these costs for an economic benefit of \$5,000, but an economic benefit of \$12,000 makes it worthwhile. Regardless of which farmer is assigned the property right, the "efficient" result will occur through negotiation.

An Illustration of the Coase Theorem

We can illustrate the Coase theorem graphically, by showing the marginal benefits and marginal costs of an economic activity that generates an externality. Suppose, for example, a factory emits effluent into a river, polluting the water supply of a downstream community. The factory is currently emitting 80 tons of effluent. If the factory were forced to reduce effluent to zero, it would have to abandon a valuable production line. Thus, we can say that the factory realizes marginal benefits from emitting pollution, and the community pays marginal costs as a result of the damage to their water supply. We can arrive at a reasonable quantitative estimate of these external costs by estimating the costs of water treatment. Both marginal costs and marginal benefits are shown in Figure 3.9.

What is the optimal solution? The emission of 80 tons of pollution clearly imposes high marginal costs on the community, while bringing the company hardly any marginal benefits for the last few tons of pollution. This is "too much" pollution. But suppose that emissions were limited to 50 tons. Marginal benefits to the company would then be equal to marginal costs to the community. A further limitation to, say, 20 tons, would result in high additional losses to the company while bringing only low additional benefits to the community.

Figure 3.9 Application of the Coase Theorem



The efficient or "optimal" solution, therefore, is at a level of pollution of 50 tons. At this level, the extra benefit to the company from production just balances the extra cost imposed on the community through pollution.[12]

The Coase theorem states that this solution can be achieved by assigning the pollution rights *either* to the company *or* to the community. Suppose first that the community has the right to say how much pollution can be emitted. You might initially think that it would not allow the company to emit any pollution. But notice in Figure 3.9 that the company would be willing to pay the community up to about $400 for the right to emit the first ton of pollution. Meanwhile, the damages to the community from the first ton of pollution are quite small, only a few dollars. So, there is a significant opportunity for a successful agreement in which the company would pay the community in order to be able to emit the first ton of pollution.

Note that this process of successful negotiation would continue as long as the marginal benefits to the company exceed the marginal damages to the community. However, the space for successful negotiation gradually declines as we move rightward on the graph. For example, after the company has already purchased the right to emit 40 tons of pollution, its marginal benefits of pollution have fallen to $200 per ton, while the marginal costs to the community have risen to $120 per ton. There is still some negotiating room for a payment that the community will accept, but not as much as when pollution was zero. Eventually, we reach a point, at 50 tons of pollution, where the company cannot offer the community enough to allow it to pollute any further. So, once the marginal benefits to the company equal the marginal costs to the community, we reach the optimal level of pollution. If there is any further pollution, the marginal costs would exceed the marginal benefits.

At this level, the marginal benefits to the company and marginal costs to the community are both equal to $150. The company will not be willing to pay any higher price than $150 for the fiftieth unit of pollution, and the community will not be willing to accept any lower price.

We can analyze the effects of this outcome using welfare analysis (as explained above, and in more detail in Appendices 3.1 and 3.2). For example, in Figure 3.9, area C represents the total costs of pollution damage at 50 tons of emissions. This area is $3,750 (using the formula for the area of a triangle, in this case 50 * 150 * ½).

If we assume that all rights to pollute sold for the same price of $150, then the community receives a total payment of $7,500 (area B + C). The total costs of pollution to the community are $3,750 (area C). So the community comes out ahead, with a net gain of $3,750.

What about the company? In purchasing the right to pollute 50 tons, it gains areas (A + B + C) in total benefits, or $13,750. But it has to pay the community $7,500 for the right to pollute 50 tons (area B + C). So the company comes out ahead by $6,250 (equal to area A), compared with not polluting at all. Considering the gains to both the company and the community, the total social welfare gain following the negotiation process is $10,000 ($3,750 + $6,250), as detailed in Table 3.3.

What if we instead assume that the company has the right to pollute as much as it wants? In this case, we start off with the firm emitting 80 tons of pollutants—gaining the maximum possible amount of benefits from polluting. Total benefits to the company would be areas (A + B + C + D), or $16,000. The total damage to the community would be areas (C + D + E + F), or $9,600. Thus total social benefits at 80 tons of pollution, prior to any negotiations, would be $16,000 − $9,600 = $6,400.

But notice that the company receives very small marginal benefits for the last ton emitted, just a few dollars. Meanwhile, the community suffered damages from the eightieth ton of $240. So, the community could pay the company to reduce its pollution, as there is a significant negotiation space where both parties could benefit. Again, the final outcome would be 50 tons of pollution, with the community paying the company $150 per ton for pollution reduction.

Table 3.3 Distribution of Benefits and Losses with Different Property Rights and Negotiation

		If Community Holds Rights		If Company Holds Rights
Gain/loss to community	+	$7,500 payment	–	$4,500 payment
	–	$3,750 environmental costs	–	$3,750 environmental costs
	+	$3,750	–	$8,250
Gain/loss to company	+	$13,750 total benefits	+	$13,750 total benefits
	–	$7,500 payment	+	$4,500 payment
	+	$6,250	+	$18,250
Total social gain	+	$10,000	+	$10,000

In this case, the company receives the financial benefits from its remaining 50 tons of pollution, or areas (A + B + C), which equal $13,750 as shown in Table 3.3. Assuming that all rights are negotiated for a price of $150 per ton, it also receives a payment of $4,500 from the community (areas D + E), for total benefits of $18,250. Note that this is higher than the $16,000 benefit it obtained from maximum pollution prior to negotiations.

The community suffers remaining damages of area C, or $3,750. It also pays the company $4,500. So its total losses are now $8,250—not a great outcome for the community, but better than its initial losses of $9,600. Note that overall net social benefits are now $18,250 – $8,250 = $10,000—the same exact outcome in terms of social benefits that we obtained when the community held the property rights.

This more formal demonstration of the Coase theorem shows that the efficient solution is reached regardless of the assignment of the property right governing pollution. Provided that right is clearly defined, the party that values it most highly will acquire it, with the result that the external costs of pollution and the economic benefits of production are balanced through the marketplace.

Note, however, that who receives the right makes a big difference in the distribution of gains and losses between the two parties (see Table 3.3). The net social benefit from production is the same in both cases, equal to area (A + B), or $10,000. But in one case, this benefit is divided between the community and the company. In the other case, the community has a net loss while the company has a large net gain.

By redistributing the right to pollute, or to control pollution, we make one party $12,000 better off and the other $12,000 worse off (to confirm this, compare the final positions of the community and the company under the two different rights allocations). The different assignments of rights are equivalent in terms of efficiency, because the final result balances marginal benefits and marginal costs, but they clearly differ in terms of equity, or social justice.

A Practical Application

An example of environmental protection using Coase theorem principles is New York City's Watershed Land Acquisition Program. The city must provide clean water to its 8.4 million residents. This can be done through building filtration plants, but the cost of building these plants can be avoided through watershed protection. By preserving land around the main water supplies for the city, the quality of the water can be maintained at a level that does not require filtration. The watersheds are located upstate, on lands not currently owned by the city. According to the U.S. Environmental Protection Agency:

> The Watershed Land Acquisition Program is a key element in the City's long-term strategy to preserve environmentally sensitive lands in its upstate watersheds. Land acquisition is a critical element of the City's ability to obtain filtration avoidance. Through this program, New York City has committed to soliciting a minimum of 355,050 acres of land over a ten-year period. The goal of the Program is for the City to acquire, from willing sellers, fee title to or conservation easements on real property determined to be water quality sensitive, undeveloped land. The land will be bought at fair market value prices and property taxes will be paid by the City. No property will be acquired by eminent domain.[13]

As in our Coase theorem example, all the transactions here are voluntary, based on private property rights. The power of eminent domain, by which a government can compel a property owner to give up land in return for compensation (see Box 3.3), is not used. New York City has made the determination that it is less expensive to pay private property owners for conservation easements, which restrict the uses of the land, or to purchase the land outright, than to construct filtration plants. This market-based solution appears to be both environmentally effective and economically efficient.

Limitations of the Coase Theorem

According to the Coase Theorem, the clear assignment of property rights appears to promise efficient solutions to problems involving externalities. In theory, if we could clearly assign property rights to *all* environmental externalities, further government intervention would not be required. Individuals and business firms would negotiate all pollution control and other environmental issues among themselves after it was clear who had the "right to pollute" or the "right to be free from pollution." Through this process, fully efficient solutions to the problem of externalities could be achieved.

This is the theoretical basis behind the idea of **free market environmentalism**. In effect, by setting up a system of property rights to the environment, this approach seeks to bring the environment into the marketplace, allowing the free market to handle issues of resource use and pollution regulation as interested parties negotiate their own solutions, without government regulation.

free market environmentalism the view that a more complete system of property rights and expanded use of market mechanisms is the best approach to solving issues of resource use and pollution control.

As we will see in dealing with specific examples in future chapters, this approach may have potential in particular cases, especially in areas like water rights. But it also has crucial limitations. What are some of the problems in simply assigning property rights and letting unregulated markets address environmental and resource problems?

We mentioned above that the Coase theorem assumes there are no transaction costs preventing efficient negotiation. In the examples that we have used, there are only two parties negotiating. What happens if, for example, 50 downstream communities are affected by pollution from a factory's effluent? The process of negotiating effluent limits will be very cumbersome, perhaps impossible. This problem would be even worse if there were several factories instead of just one. Thus, the efficient outcome may not be reachable because of significant transaction costs.

Box 3.3
PROPERTY RIGHTS AND ENVIRONMENTAL REGULATION

Under the principle of eminent domain, governments are permitted to appropriate private property for public purposes. However, the Fifth Amendment of the U.S. Constitution requires that the property owner be fairly compensated. Specifically, the Fifth Amendment concludes with the statement "nor shall private property be taken for public use, without just compensation."

An action by a government that deprives someone of his or her property rights is referred to as a "takings." In cases in which the property owner is deprived of all property rights, the Constitution clearly orders full compensation. For example, if a state government decides to build a highway through a parcel of private property, the landowner must be paid the fair market value of the property.

A more ambiguous situation arises when actions by a government limit the uses of property and, consequently, reduce the value of property. Instances of government regulations reducing the value of private property are often called "regulatory takings." For example, if a new law is created that regulates timber harvesting and reduces the value of private forests, are the landowners entitled to compensation under the Fifth Amendment?

The most notable case concerning a regulatory taking is *Lucas v. South Carolina Coastal Council*. David Lucas, a real estate developer, purchased two oceanfront lots in 1986 and planned to construct vacation homes. However, in 1988 the South Carolina state legislature enacted the Beachfront Management Act, which prohibited Lucas from building any permanent structures on the property. Lucas filed suit claiming that the legislation had deprived him of all "economically viable use" of his property.

A trial court ruled in Lucas's favor, concluding that the legislation had rendered his property "valueless" and awarded him $1.2 million in damages. However, the South Carolina Supreme Court reversed this decision. It ruled that further construction in the area posed a significant threat to a public resource and asserted that in cases in which a regulation is intended to prevent "harmful or noxious uses" of private property, no compensation is required.

The case was appealed to the U.S. Supreme Court. Although the Supreme Court overturned the state court ruling, ruling in favor of Lucas, it delineated a distinction between total and partial takings. Compensation is necessary only in cases of total takings—when a regulation deprives a property owner of "all economically beneficial uses." If a regulation merely reduces a property's value, then compensation is not required.

In essence, this ruling represented a victory for environmental regulation because cases of total takings are rare. Partial takings as a result of government regulations, however, are common. A requirement of compensation for partial takings would have created a legal and technical morass that would render many environmental laws ineffective. Still, partial takings can result in significant costs to individuals, and the debate continues over equity when private costs are necessary to achieve the public good. Legal cases since *Lucas* have affirmed the "total takings" principle with slight variations, with the Supreme Court, for example, ruling in *Palazzolo v. Rhode Island* (2001) that compensation was required in a case where virtually all uses of land had been prohibited, even if the land retained some small amount of value.

Sources: Ausness, 1995; Hollingsworth, 1994; Johnson, 1994; Eagle, 2009.

Free-Rider and Holdout Effects

Another problem may arise with a large number of affected communities. Suppose that we assign the factory the right to pollute. The communities can then offer compensation for reducing pollution. But which community will pay what share? Unless all 50 can agree, it might prove impossible to make a specific offer to the company. No single community, or group of communities, is likely to step forward to pay the whole bill. In fact, there is likely to be a tendency to hang back, waiting for other communities to "buy off" the factory—and thus gain pollution control benefits for free. This barrier to successful negotiations is known as the **free-rider effect**, in which there is a tendency not to pay one's share of the costs but still attempt to receive the benefits.

free-rider effect the incentive for people to avoid paying for a resource when the benefits they obtain from the resource are unaffected by whether they pay; results in the undersupply of public goods.

holdout effect the ability of a single entity to hinder a multiparty agreement by making disproportionate demands.

A similar problem arises if the communities are given the "right to be free from pollution" and the factory must compensate them for any pollution emitted. Who will determine which community gets how much compensation? Because all are situated on the same river, any single community can exercise a kind of veto power. Suppose that 49 communities have hammered out an agreement with the company on permissible pollution levels and compensation. The fiftieth community can demand a much higher rate of compensation, for if it withholds consent, the entire agreement will fail, and the company will be restricted to zero pollution (i.e., forced to shut down). This parallel to the free-rider effect is known as the **holdout effect**.

When large numbers of parties are affected, the Coase theorem generally cannot be applied. In this case, some form of government intervention is required, such as regulation or a Pigovian tax. The state or federal government could set a standard for a water-borne effluent or a tax per unit of effluent. This would not be a pure market solution (although a tax does have its impact through market processes) because government officials must decide on the strictness of regulation or the level of tax.

Issues of Equity and Distribution

Other lines of criticism of the Coase theorem concern its effects on equity. Suppose that in our original example the community suffering from pollution is a low-income community. Even if the water pollution is causing serious health impacts, which could be valued at many millions of dollars, the community may simply be unable to "buy off" the polluter. In this case, the market solution is clearly not independent of the assignment of property rights. Pollution levels will be significantly higher if the right to pollute is assigned to the company.

It is also possible that, even if the right is assigned to the community, poor communities will accept location of toxic waste dumps and other polluting facilities out of a desperate need for compensatory funds. While this is apparently consistent with the Coase theorem (it is a voluntary transaction), many people believe that communities should not be forced to trade the health of their residents for needed funds. An important criticism of free market environmentalism is that under a pure market system, poorer communities and individuals will generally bear the heaviest burden of environmental costs (see Box 3.4).

A similar issue relates to preservation of open space. Wealthy communities can afford to buy up open space for preservation, while poor communities cannot. If communities are allowed to use zoning to preserve wetlands and natural areas, poor communities, too, will be able to protect their environment, because passing a zoning regulation has zero cost other than for enforcement.

Box 3.4
ENVIRONMENTAL JUSTICE

As defined by the U.S. Environmental Protection Agency, "**Environmental justice** is the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies."

Issues of environmental injustice concern both economic status and also political power. Low-income communities and minorities often lack the political clout to affect decision-making at the local and state level, and as a result, many decisions can be made without having their best interests in mind. The result can be that the poorest parts of the population end up carrying the highest environmental burden.

This was the case in Flint, Michigan, where a crisis of water contamination arose when officials decided to switch the city's water source from the Detroit Water and Sewerage Department water to the Flint River in April 2014. The explicit goal was to save millions of dollars for the municipal budget of Flint, which was on the brink of financial collapse. The corrosive Flint River water was not treated properly, causing lead from aging pipes to leach into the water supply, resulting in highly elevated levels of this heavy metal neurotoxin.

In Flint, between 6,000 and 12,000 children have been exposed to drinking water with dangerously elevated levels of lead, and they may experience a range of serious health problems. Flint is a low-income community, 84 percent black, and the agonizingly slow government response to the crisis was widely considered as a prime example of environmental racism and injustice.

Sources: U.S. Environmental Protection Agency, https://www.epa.gov/environmentaljustice; John Eligon, "A Question of Environmental Racism in Flint". *New York Times*, Jan. 21, 2016.

Another point to note in considering the limitations of the Coase theorem is the issue of environmental impacts on nonhuman life forms and ecological systems. Our examples so far have assumed that environmental damage affects specific individuals or businesses. What about environmental damage that affects no individual directly but threatens plant or animal species with extinction? What if a certain pesticide is harmless to humans but lethal to birds? Who will step into the marketplace to defend the preservation of nonhuman species? No individual or business firm is likely to do so, except on a relatively small scale.

environmental justice the fair treatment of people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies.

Consider, for example, the activities of a group like the Nature Conservancy, which buys up ecologically valuable tracts of land in order to preserve them. Here is an example of an organization that *is* prepared to pay to save the environment. But its purchases can reach only a tiny proportion of the natural areas threatened with destruction through development, intensive farming, and other economic activities. In the "dollar vote" marketplace, purely ecological interests will almost always lose out to economic interests. Ecological economists seek ways to ensure that the value of these interests are adequately expressed, either in monetary or ethical terms.

We should also note that property rights are typically limited to the current generation. What about the rights of the next generation? Many environmental issues have long-term implications. Rights to nonrenewable resources can be assigned today, but those resources will be used up at some time in the future. Ecosystems destruction and species loss today will have implications for all future generations. The important issue of resource allocation over time is addressed in Chapter 5. Long-term environmental impacts are also vital to the analysis of fisheries, forests, water (dealt with in Chapters 18, 19, and 20) and climate change (presented in Chapters 12 and 13).

In some cases, property rights are simply inappropriate tools for dealing with environmental problems. It may be impossible, for example, to establish property rights to the atmosphere or to the open ocean. When we confront problems such as global warming, ocean pollution, the decline of fish stocks, or endangered species, we find that the system of private property rights, which has evolved as a basis for economic systems, cannot be fully extended to ecosystems. It may be possible to use market transactions, such as tradable permits for air emissions or fishing rights, but these only apply to a limited subset of ecosystem functions. In many cases, some other techniques of economic analysis will be helpful in considering the interaction between human economic activity and aspects of the broader ecosystem. We consider some of these analyses next in Chapter 4.

Summary

Many economic activities have significant external effects—impacts on people who are not directly involved in the activity. Pollution from automobile use is an example. The costs of these external impacts are not reflected in the market price, leading to an excessive production of goods with negative externalities and an economically inefficient outcome.

One approach to pollution control is to internalize external costs using a tax or other market-based instrument that requires producers and consumers of the polluting good to take these costs into account. In general, the use of such a tax will raise the price and reduce the quantity produced of the good, thereby also reducing pollution. In so doing, it shifts the market equilibrium to a socially more desirable result. In theory, a tax that exactly reflects external costs could achieve a social optimum, but it is often difficult to establish a proper valuation for negative externalities.

Not all externalities are negative. Positive externalities result when economic activities bring benefits to others not directly involved in the transaction. Preservation of open land benefits those who live nearby directly, often raising their property values. The use of solar energy benefits society as it reduces pollution levels. When a positive externality exists, there is an economic case for a subsidy to increase the market provision of the good.

An alternative to the use of a tax is the assignment of property rights to externalities. If there is a clear legal right either to emit a certain amount of pollution or to prevent others from emitting pollution, a market in "rights to pollute" can develop according to the Coase theorem. However, this solution depends on the ability of firms and individuals to trade these pollution rights with relatively low transaction costs. Where large numbers of people are affected, or where the environmental damages are not easy to define in monetary terms, this approach is not effective. It also raises significant questions of equity, because under a market system the poor generally bear a heavier burden of pollution.

Key Terms and Concepts

Coase theorem

economic efficiency

elasticities of supply and demand

equilibrium price

external costs

free market environmentalism

free-rider effect

holdout effect

internalizing externalities

marginal benefit

marginal cost
negative externality
optimal pollution
Pigovian tax
polluter pays principle
positive externalities
social marginal cost curve
socially efficient
subsidy
transaction costs
upstream tax
welfare analysis

Discussion Questions

1. "Solving the problems of environmental economics is simple. It is just a matter of internalizing the externalities." What is your reaction to this statement? Does the theory of externalities apply to most or all environmental issues? What are some of the practical problems involved in internalizing externalities? Can you think of some examples in which the principle works well and others in which it is more problematic?
2. A pollution tax is one policy instrument for internalizing externalities. Discuss the different economic policy implications of a tax on automobiles, on gasoline, or on tailpipe emission levels as measured at an auto inspection. Which one would be the most cost-efficient? Which do you think would be most effective in reducing pollution levels?

Exercises

1. Consider the following supply-and-demand schedule for steel:

Price per ton ($)	20	40	60	80	100	120	140	160	180
Q_D (million tons)	200	180	160	140	120	100	80	60	40
Q_S (million tons)	20	60	100	140	180	220	260	300	340

Pollution from steel production is estimated to create an external cost of $60 per ton.

a) Using a supply-and-demand graph to support your answer, what is the unregulated market equilibrium (price and quantity) in the steel market?
b) Add the external costs to your graph from part (a). What is the socially optimal outcome in the steel market (price and quantity)? What economic policy could be implemented to achieve the social optimum?
c) Using either your previous graph or creating a new one, use welfare analysis to demonstrate that total social welfare is greater at the social optimum than with the unregulated market outcome.

2. A chemical factory is located next to a farm. Airborne emissions from the chemical factory damage crops on the farm. The marginal benefits of emissions to the factory and the marginal costs of damage to the farmer are as follows:

Quantity of emissions	100	200	300	400	500	600	700	800	900
Marginal benefit to factory ($000)	320	280	240	200	160	120	80	40	0
Marginal cost to farmer ($000)	110	130	150	170	190	210	230	250	270

a) Suppose that there are no laws preventing the chemical factory from emitting pollution. How much pollution will it emit? Briefly explain why.
b) From an economic point of view, what is the socially optimal level of emissions from the chemical factory? Briefly explain why, using a graph to support your answer.
c) Again, assuming there are no laws preventing the factory from polluting, describe how the socially efficient outcome could be achieved using the Coase Theorem.
d) While the Coase Theorem solution from part (c) is economically efficient, do you think it is equitable? Briefly explain why or why not.

3. (If Appendix 3.2 is covered, "Negative Externalities—A Mathematical Approach.") Suppose the demand curve for an electronic tablet is:

$$P_d = 200 - 3\,Q$$

where Q is the number demanded in thousands. The supply curve is:

$$P_s = 20 + 3\,Q$$

where, again, Q is measured in thousands. Production of the tablets, considering the materials used, the wastes created, transportation, and packing results in $30 of external costs per tablet.

a) Solve for the equilibrium price and quantity in the tablet market without any regulation, both algebraically and using a supply-and-demand graph.
b) What is total social welfare in the tablet market without any regulation? Solve for consumer surplus, producer surplus, and the externality damage algebraically. (Be careful about the units.) Also show these areas in your graph from part (a).
c) If the correct Pigovian tax is instituted, what will be the new equilibrium price and quantity in the tablet market? Solve algebraically and also show this on a graph (the same graph from above or a new graph).
d) What is total social welfare in the tablet market with the correct Pigovian tax? Solve for consumer surplus, producer surplus, the externality damage, and the tax revenues algebraically. Also show these areas in your graph from part (c).

Notes

1. U.S. EPA, Global Greenhouse Gas Emissions Data, http://www.epa.gov/climatechange/ghgemissions/global.html.
2. WHO, 2013.
3. Parry *et al.*, 2007.
4. Becker *et al.*, 2012.
5. If we imposed the tax on the consumer instead of the producer, we would reach the same result as we obtain in the text.
6. Note that in our example, the externality damage is constant per automobile produced. If the externality damages were not constant, we would set the tax equal to the marginal externality damage at the optimal level of automobile production.

7. Trucost, 2013.
8. Authors' calculations from World Development Indicators database.
9. Trucost, 2013.
10. UNEP, 2011.
11. Coase, 1960.
12. Note that the marginal benefit equation for the company in this example is MB = 400 – 5T, where T is tons of pollution. The marginal cost (damage) function for the community is MC = 3T. Thus the point of intersection is found by setting the two equations equal, 400 – 5T = 3T, or T = 50.
13. www.epa.gov/region02/water/nycshed/protprs.htm#land.

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Web Sites

1. **www.journals.elsevier.com/journal-of-environmental-economics-and-management/.** Web site for the *Journal of Environmental Economics and Management*, with articles on environmental economic theory and practice.

2. **http://reep.oxfordjournals.org.** Web site for the *Review of Environmental Economics and Policy*, with articles on the application of environmental economic concepts to practical cases of environmental policy; the journal "aims to fill the gap between traditional academic journals and the general interest press by providing a widely accessible yet scholarly source for the latest thinking on environmental economics and related policy."

3. **www.iisd.org/publications/.** A library of publications by the International Institute for Sustainable Development, including many publications on using economic instruments to promote environmentally-sound economic development.

4. **http://chicagopolicyreview.org/2012/02/15/when-costs-outweigh-benefits-accounting-for-environmental-externalities/.** A paper estimating the cost of environmental externalities in major industries to the U.S. economy, indicating that "the cost of environmental externalities in several industries exceeds the value they add to the economy."

APPENDIX 3.1: SUPPLY, DEMAND, AND WELFARE ANALYSIS

This text presupposes that you have had an introductory economics course. But if you have not, or if your basic economic theory is a little rusty, then this appendix provides you with the background microeconomic knowledge you will need for this book.

Economists use models to help them explain complex phenomena. A model is a scientific tool that helps us understand something by focusing on certain aspects of reality yet ignoring others. No model can consider every possible factor that might be relevant, so scientists make simplifying assumptions. A scientific model can take the form of a simplified story, a graph, a figure, or a set of equations. One of the most powerful and widely used models in economics concerns the interaction of supply and demand. Based on several simplifying assumptions, this model provides us with insights about the changes we can expect when certain things happen, as well as what types of economic policies are the most appropriate in different circumstances.

The Theory of Demand

The theory of demand considers how consumer demand for goods and services changes as a result of changes in prices and other relevant variables. In this appendix, we use the market for gasoline as an example. Obviously, many factors affect consumer demand for gasoline, so we start by making a simplifying assumption. For now, let us consider only how consumer demand for gas changes when the price of gas changes—all other relevant factors are assumed to be held constant. Economists use the Latin term *ceteris paribus*, meaning "all other things equal" or "all else being equal," to isolate the influence of only one or a few variables.

> **law of demand** the economic theory that the quantity of a good or service demanded will decrease as the price increases.

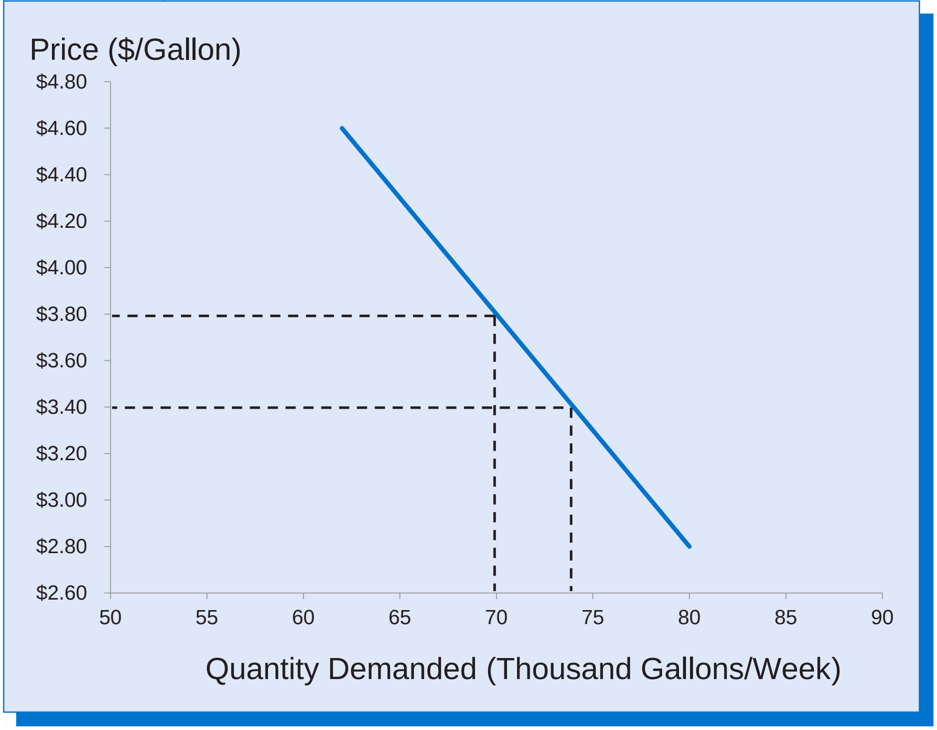
How will the quantity of gas demanded by consumers change as the price of gas changes? The **law of demand** states that as the price of a good or service increases, consumers will demand less of it, *ceteris paribus*. We could conversely state the law of demand thus: Consumers demand more of a good or service when the price of it falls. This inverse relationship between the price of something and the quantity demanded can be expressed a couple of ways. One is a demand schedule—a table showing the quantity of a specific good or service demanded at different prices. The other way is to use a graph to illustrate a demand curve—just the graphical representation of a demand schedule. The convention among economists is to put the quantity demanded on the horizontal axis (the x-axis) and price on the vertical axis (the y-axis).

Suppose that we have collected some data about how much gasoline consumers in a particular metropolitan area demand at different prices. This hypothetical demand schedule is presented in Table A3.1. We can see that as the price of gas rises, people demand less of it. The data in Table A3.1 are expressed graphically, as a demand curve, in Figure A3.1. Notice that the demand curve slopes down as we move to the right, as we would expect according to the law of demand.

Table A3.1 Demand Schedule for Gasoline

Price ($/gal.)	$2.80	$3.00	$3.20	$3.40	$3.60	$3.80	$4.00	$4.20	$4.40	$4.60
Quantity demanded (thousand gal/week)	80	78	76	74	72	70	68	66	64	62

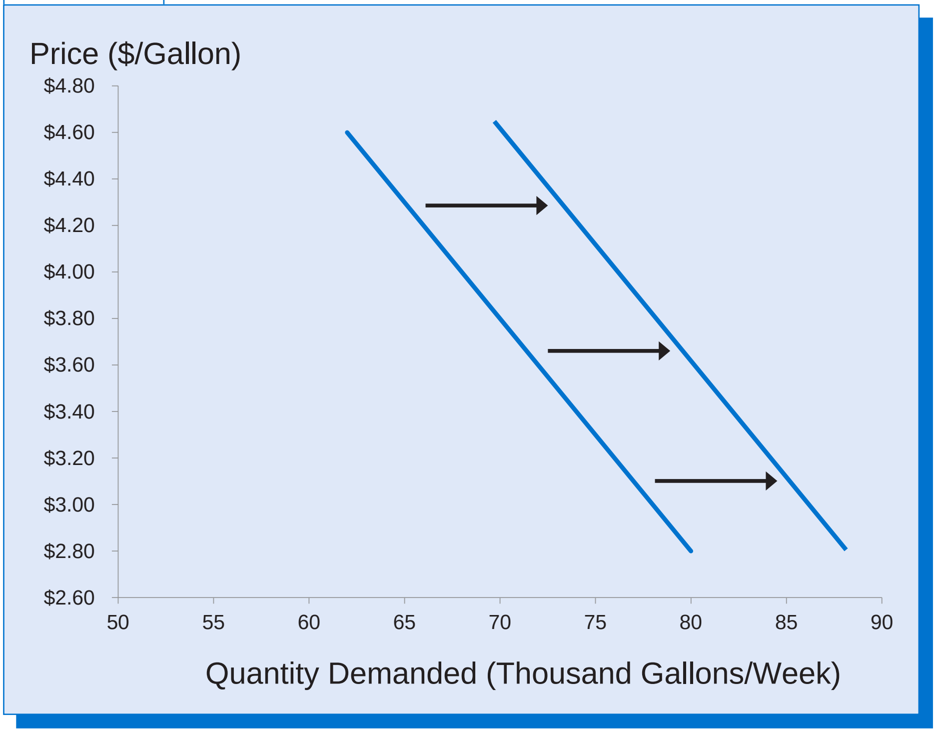
Figure A3.1 Demand Curve for Gasoline



We can see in Figure A3.1 that at a price of $3.40 per gallon, consumers in the area will purchase 74,000 gallons of gas per week. Suppose that the price rises to $3.80 per gallon. At the higher price, we see that consumers decide to purchase less gas, 70,000 gallons per week. We call this movement along a demand curve at different prices a *change in the quantity demanded*. This is different from what economists call a *change in demand*. A change in demand occurs when the entire demand curve shifts.

What would cause the entire demand curve to shift? First, we need to realize that a change in the price of gasoline will *not* cause the demand curve to shift, it will only cause consumers to move along the demand curve in Figure A3.1 (i.e., a change in the quantity demanded). Our demand curve in Figure A3.1 is stable, as long as we assume that no other relevant factors are changing—the *ceteris paribus* assumption. To expand our model, let us consider several factors that would cause the entire demand curve to shift. One factor is income. If the consumers' incomes were to rise, many would decide to purchase more gas at the same price. Higher incomes would result in a change in demand. This is shown in Figure A3.2 where the entire demand curve shifts to the right.[1]

Figure A3.2 A Change in Demand



Another factor that would cause a change in demand is a change in the price of related goods. In our example of the demand for gas, suppose that the price of public transportation increases significantly. This would cause the demand for gas to increase (shift to the right) as some people decide to drive their own vehicles because public transportation is now too expensive for them. A change in consumer preferences could also cause the demand curve for gas to shift. For example, if consumers start preferring smaller, fuel-efficient vehicles, this would cause a decrease in the demand for gas. A significant change in the number of people driving would also cause a change in the demand for gas. In what direction do you think the demand curve for gas would shift if the population of our metropolitan area were to decrease by 20 percent? Can you think of any other factors that would also cause a demand curve to shift?

The Theory of Supply

The next step in our analysis is to consider the other side of the market. The theory of supply considers how suppliers respond to changes in the price of a good or service they offer, or changes in other relevant factors. While low prices appeal to consumers looking for a bargain, high prices appeal to suppliers looking to make profits. As you might expect, the **law of supply** is the opposite of the law of demand. The law of supply states that as the price of a good or service increases, suppliers will choose to offer more of it, *ceteris paribus*. According to the law of supply, price and the quantity supplied change in the same direction.

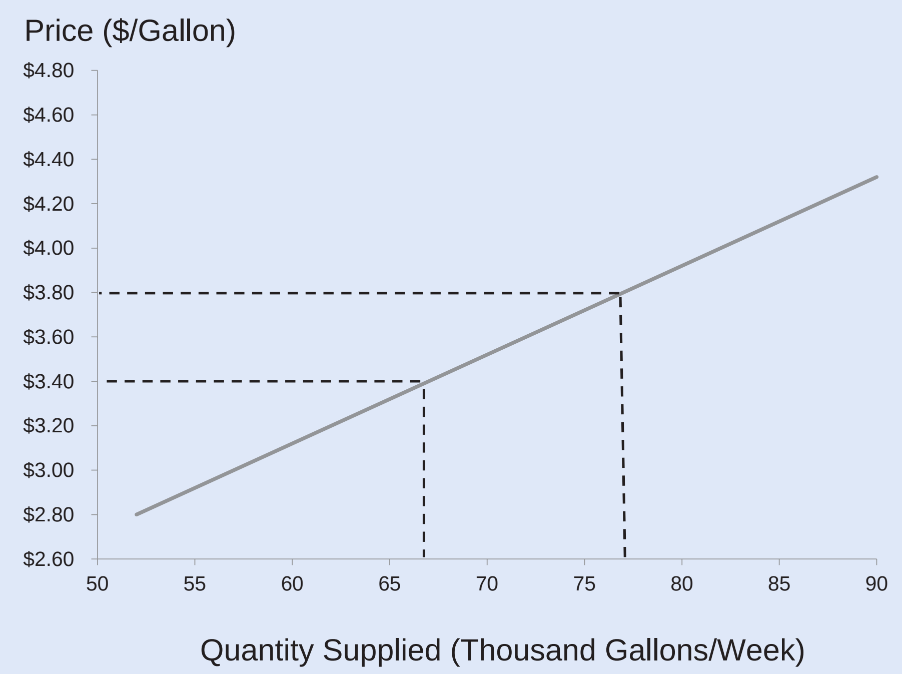
law of supply the economic theory that the quantity of a good or service supplied will increase as the price increases.

Once again, we can express the relationship between price and the quantity supplied using both tables and graphs. Table A3.2 illustrates a supply schedule for gas, with the quantity supplied increasing as the

Table A3.2 Supply Schedule for Gasoline

Price ($/gal.)	$2.80	$3.00	$3.20	$3.40	$3.60	$3.80	$4.00	$4.20	$4.40	$4.60
Quantity demanded (thousand gal/week)	52	57	62	67	72	77	82	87	92	97

Figure A3.3 Supply Curve for Gasoline

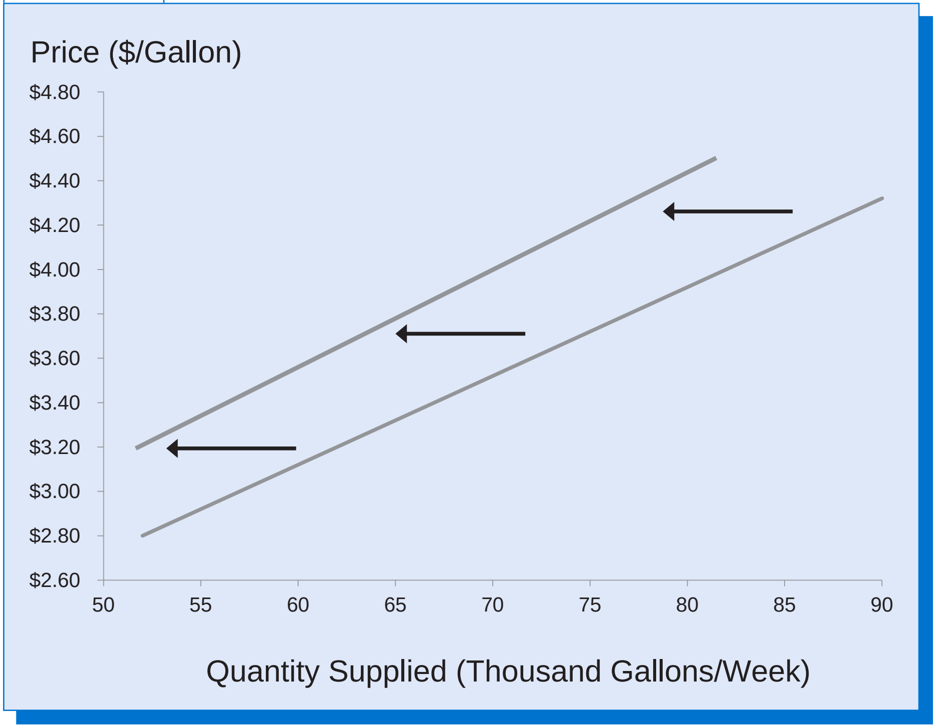


price of gas increases. Figure A3.3 simply converts the data in Table A3.2 into a graph. Notice that the supply curve slopes upward as we move to the right.

There is also a distinction between a *change in the quantity supplied* and a *change in supply*. A change in the quantity supplied occurs when we move along a supply curve as the price of the good or service changes. This is shown in Figure A3.3. We see that at a price of $3.40, suppliers are willing to supply 67,000 gallons of gas. But if the price were to increase to $3.80, the quantity supplied would increase to 77,000 gallons per week.

A change in supply occurs when the entire supply curve shifts. Again, several different factors might cause a supply curve to shift. One is a change in the price of input goods and services. For example, an increase in the wages paid to gasoline company employees would cause suppliers to raise the price that they charge for gas, meaning a shift in the supply curve to the left, as illustrated in Figure A3.4. Another factor that would cause a change in supply is a change in production technology. Suppose that an innovation reduces the costs of gasoline refining. In which direction would the supply curve shift in this case? Can you think of other factors which would cause a change in supply?

Figure A3.4 A Change in Supply



Market Analysis

We can now bring together both sides of the gasoline market. The price of gasoline is determined by the interaction of consumers and suppliers. We can illustrate this interaction by putting our demand and supply curves on the same graph, as shown in Figure A3.5. We can use this figure to determine what the price of gas will be and how much will be sold. First, suppose the price of gas was initially $3.80 per gallon. We see in Figure A3.5 that at this price the quantity supplied exceeds the quantity demanded. We call this situation a **surplus** because suppliers have more gas than consumers are willing to buy. Rather than dumping the excess gas, suppliers will lower their price in order to attract more customers. So, in the case of a surplus, we expect a downward pressure on prices.

> **surplus** a market situation in which the quantity supplied exceeds the quantity demanded.

What if the initial price were instead $3.20 per gallon? We see in Figure A3.5 that at this price the quantity demanded exceeds the quantity suppliers are willing to supply. Suppliers will notice this excess demand and realize they can raise their prices. So, in the case of a **shortage**, there will be upward pressure on prices.

> **shortage** a market situation in which the quantity demanded exceeds the quantity supplied.
>
> **market equilibrium** the market outcome where the quantity demanded equals the quantity supplied.

When a surplus or shortage exists, the market will adjust, attempting to eliminate the excess supply or excess demand. This adjustment will continue until we reach a price where the quantity demanded equals the quantity supplied. Only at this price is there no pressure for further market adjustment, *ceteris paribus*. We see in Figure A3.5 that this occurs at a price of $3.60 per gallon. At this price, both the quantity demand and the quantity supplied are 72,000 gallons per week. Economists use the term **market equilibrium** to describe a market that has reached this stable situation.

Figure A3.5 Equilibrium in the Market for Gasoline

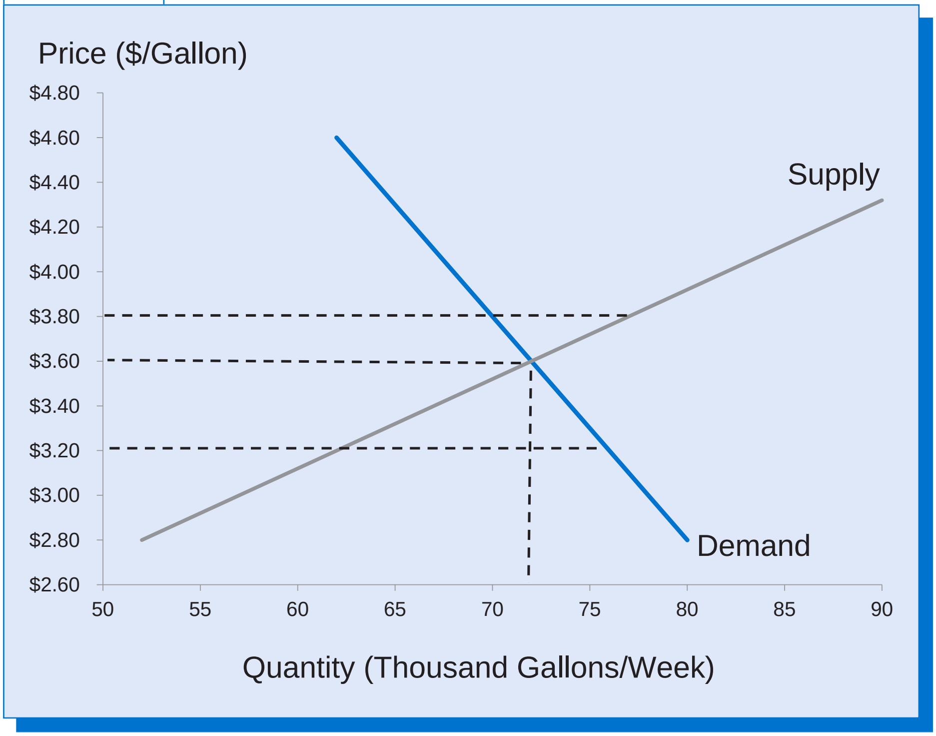
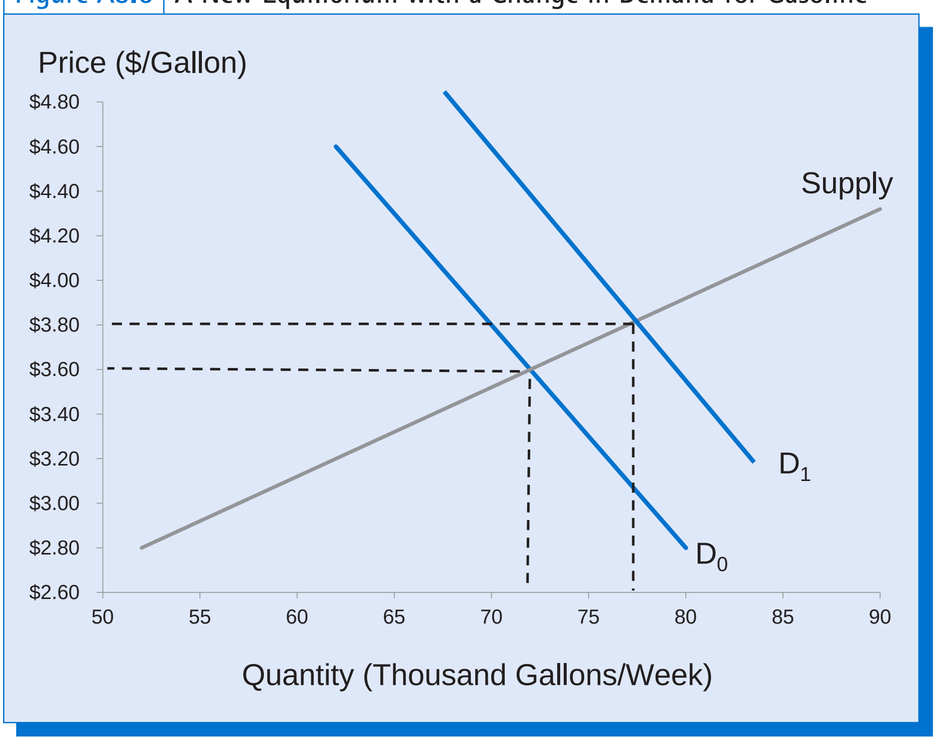


Figure A3.6 A New Equilibrium with a Change in Demand for Gasoline



A market in equilibrium is stable as long as all other relevant factors stay the same, such as consumer incomes, the prices of related goods, and production technology. Changes in these variables will cause one (or both) curve(s) to shift and result in a new equilibrium, as illustrated in Figure A3.6. Assume that an increase in consumer income causes the demand curve for gas to shift from D_0 to D_1. This results in a new market equilibrium with a higher price and an increase in the quantity of gas sold. You can test yourself by figuring out what happens to the equilibrium price and quantity when the demand curve shifts in the opposite direction and when the supply curve shifts.

Elasticity of Demand and Supply

Demand and supply curves indicate consumers' and suppliers' responsiveness to changes in price. While we expect all demand curves to slope downward and all supply curves to slope upward, responses to price changes can be large or small. Consider again how consumers would respond to an increase in the price of gasoline. Consumers would buy less gas but, at least in the short term, probably not that much less because they generally have fixed commutes to work, cannot easily buy a new vehicle, and so on. The degree of consumer responsiveness to a change in the price of a good or service is determined by the **price elasticity of demand**.

price elasticity of demand the responsiveness of the quantity demanded to price, equal to the percentage change in quantity demanded divided by the percentage change in price.

The demand for a good is relatively *price inelastic* if the quantity demanded changes little as the price changes. This can be illustrated graphically by a relatively steep demand curve. The formal expression of demand elasticity in mathematical terms is:

$$\textit{Elasticity of demand} = \frac{\textit{Percent change in quantity demanded}}{\textit{Percent change in price}}$$

Because the quantity demanded moves in the opposite direction of the price, demand elasticity is a negative number. Gasoline is an example of a good with a demand that is price inelastic. But the demand for a good is relatively *price elastic* if the quantity demanded changes a great deal as the price changes (the demand curve would be relatively flat). Can you think of some goods which have relatively elastic demand curves?

We can also talk about the **price elasticity of supply**. The supply of a good is considered price inelastic if the quantity supplied changes little as the price changes. A price-elastic supply curve would indicate a relatively large change in the quantity supplied with a change in the price. The mathematical expression for elasticity of supply is the same as for elasticity of demand, but because quantity and price move in the same direction, supply elasticity is positive.

price elasticity of supply the responsiveness of the quantity supplied to price, equal to the percentage change in quantity supplied divided by the percentage change in price.

Notice that the price elasticity of demand and supply can change as we consider a longer period. In the short term, the demand and supply curves for gasoline are relatively inelastic. But when we consider a longer time frame, consumers can respond to an increase in gas prices by moving closer to work or buying a more fuel-efficient vehicle, and suppliers can build new refineries or drill more oil wells. So the price elasticity of demand and supply for gasoline will be more elastic over a longer period.

Welfare Analysis

The final topic we consider in this appendix is welfare analysis. Welfare analysis looks at the benefits that consumers and suppliers obtain from economic transactions. Using welfare analysis, our supply-and-demand model becomes a powerful tool for policy analysis. Our understanding of welfare analysis begins with a more detailed look at demand and supply curves.

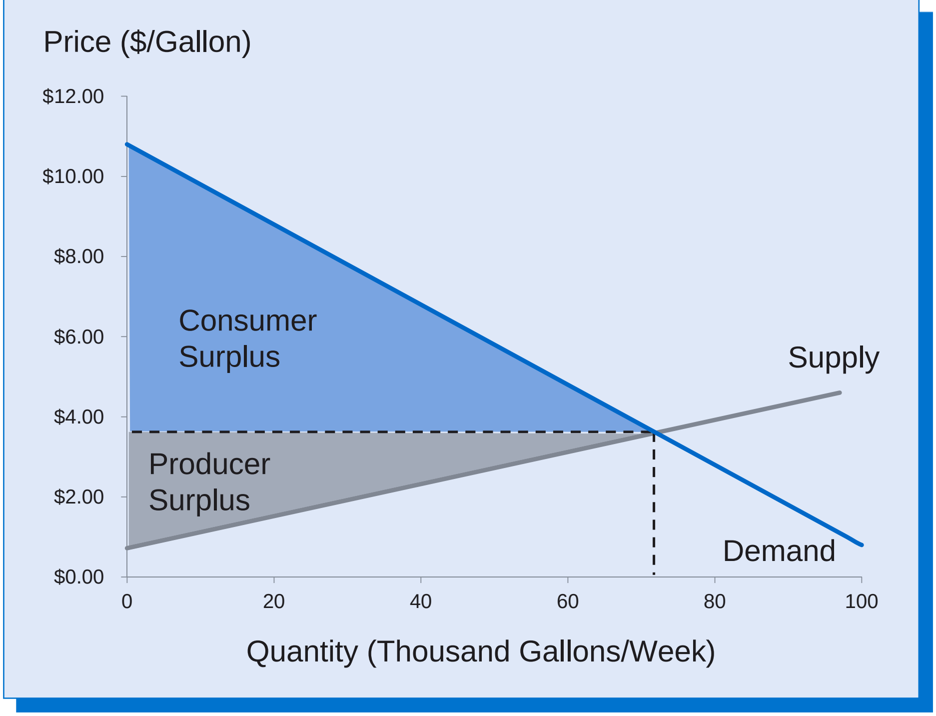
Why do people buy things? Economists assume that people will not purchase a good or service unless the benefits that they obtain from the purchase exceed what they have to pay for it. While the cost of something is expressed in dollars, quantifying benefits in dollar terms is not obvious. Economists define the net benefits a consumer obtains from a purchase as their maximum **willingness to pay** less the price they actually have to pay. For example, if someone is willing to spend a maximum of $30 for a particular shirt yet the actual price is $24, then he or she obtains a net benefit of $6 by buying it. This net benefit is called **consumer surplus**.

willingness to pay (WTP) the maximum amount of money people are willing to pay for a good or service that increases their well-being.

consumer surplus the net benefit to a consumer from a purchase; equal to their maximum willingness to pay minus price.

Note that if the price of the shirt were instead $32, the consumer would not purchase it because the costs are greater than their benefits. When we observe people purchasing goods or services, we conclude that they are doing so because the benefits that they obtain exceed their costs. If the price of a particular item rises, some people will decide not to purchase it—buying other things instead or saving their money. If the price rises further, more people will drop out of the market because the cost exceeds their maximum willingness to pay. In other words, a demand curve can also be viewed as a maximum willingness-to-pay curve.

Figure A3.7 Consumer and Producer Surplus



We can now look at Figure A3.7, which shows the demand and supply curve for gasoline. The equilibrium values are the same as before ($3.60 per gal. and 72,000 gallons sold), but the demand and supply curves have been extended to the *y*-axis. Given that the demand curve is a maximum willingness-to-pay curve, the vertical difference between the demand curve and the equilibrium price is consumer surplus. Total consumer surplus in the gasoline market is indicated by the blue triangle in Figure A3.7.

We can also look at the supply curve in more detail. Economists assume that suppliers will supply an item only if the price exceeds their costs of production—in other words, if they can obtain a profit. The supply curve shows how much is needed to cover production costs. This explains the upward slope; as production increases, costs tend to rise. (At low levels of production, costs might fall as production increases, a phenomenon known as **economies of scale**. But eventually, costs are likely to rise as raw materials run short, workers are paid overtime, and so forth.) In effect, the supply curve tells us how much it costs to supply each additional unit of an item. The cost to supply *one more* unit of a good is called the marginal cost. In other words, a supply curve is a **marginal cost** curve.

economies of scale an expanded level of output reduces per-unit production costs.

marginal cost the cost of producing one more unit of a good or service.

producer surplus the net benefits of a market transaction to producers, equal to the selling price minus production costs (i.e., profits).

Economists define the benefits that producers obtain from selling an item as **producer surplus**. Producer surplus is calculated as the selling price minus the cost of production. Once again, we can look at our supply and demand graph to visualize producer surplus. We see in Figure A3.7 that producer surplus is the lower triangle between the supply curve and the equilibrium price. The total net benefits from a market are simply the sum of consumer and producer surplus.

We can use welfare analysis to determine the impacts of various government policies, such as taxes and price controls. While welfare analysis can indicate whether a policy increases or decreases net benefits, it normally does not tell us about the distribution of costs and benefits or the broader social and ecological impacts. Clearly, other impacts must be considered if we want to conduct a complete policy analysis.

APPENDIX 3.2: EXTERNALITY ANALYSIS: ADVANCED MATERIAL

Formal Presentation of Externality Welfare Analysis

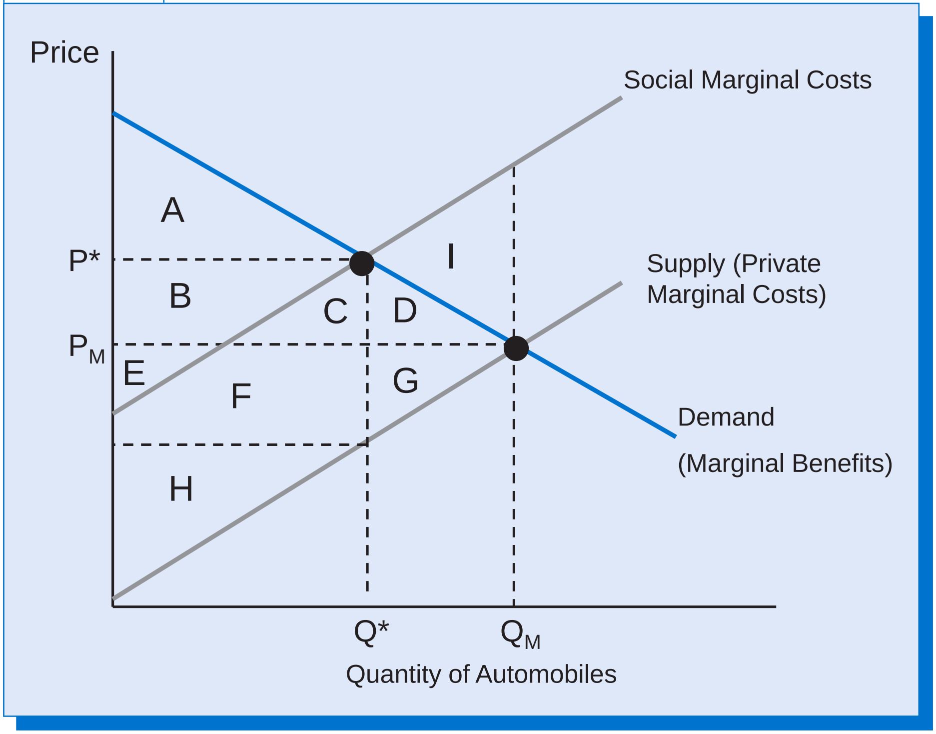
In this appendix, we present a more formal analysis of externalities, starting with negative externalities. Figure A3.8 is similar to Figure 3.7, which shows the market for automobiles in the presence of a negative externality. The net social welfare of the automobile market is the market benefits (the sum of consumer and producer surplus) minus the external costs. Consumer surplus at the market equilibrium Q_M in Figure A3.8 is:

$$CS = A + B + C + D.$$

The producer surplus at the market equilibrium Q_M is:

$$PS = E + F + G + H.$$

Figure A3.8 Welfare Analysis of Automobile Market with Externalities



The vertical distance between the social marginal costs and the private marginal costs is the externality damage per automobile. These externality damages accrue for every automobile sold, up to the market equilibrium of Q_M. Thus the total externality damage is the parallelogram between the two cost curves up to Q_M, or:

$$Externality = C + D + F + G + H + I.$$

Since the externality damage represents a cost, to determine the net social welfare we need to subtract these costs from the market benefits. Thus, the net social welfare of the unregulated automobile market is:

$$Net\ Benefits = (A + B + C + D) + (E + F + G + H) - (C + D + F + G + H + I).$$

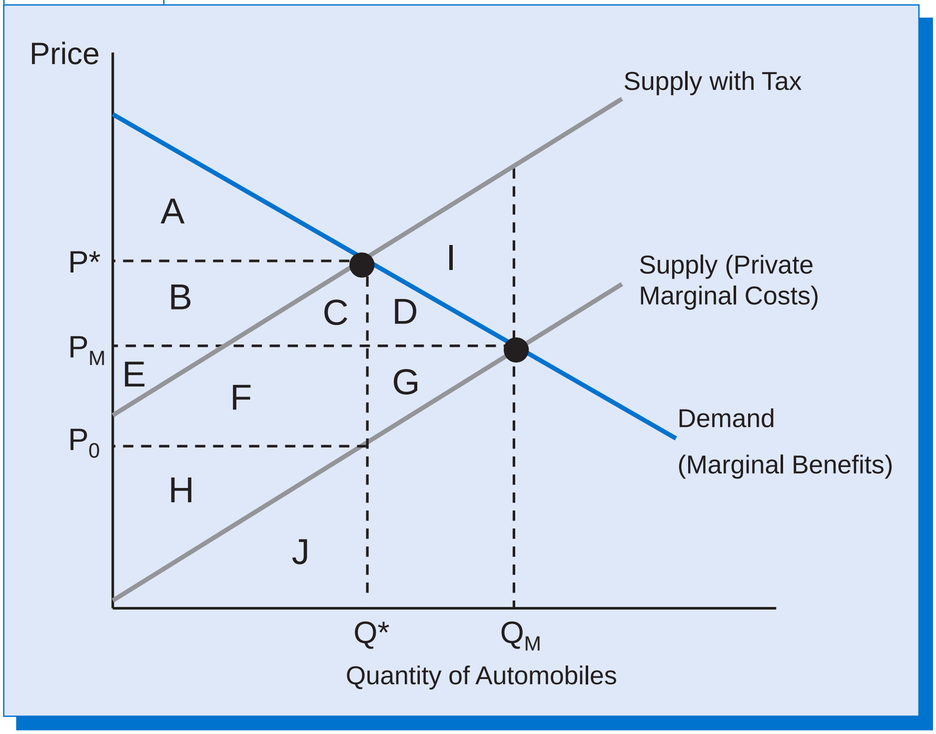
Canceling out the positive and negative terms, we are left with:

$$Net\ Benefits = A + B + E - I.$$

Next, we determine net social welfare with a Pigovian tax that fully internalizes the externality, shown in Figure A3.9.

With a new price of *P**, the new consumer surplus is simply area A. Note that this is less than the original consumer surplus of (A + B + C + D). So, the tax has raised prices and clearly reduced the welfare of automobile consumers, which makes sense given that consumers generally do not like taxes, *ceteris paribus*.

Figure A3.9 Welfare Analysis of Automobile Market with Pigovian Tax



The effect on producer surplus is a little more difficult to determine. We know that total revenue to producers is simply price times quantity, or ($P*$ times $Q*$). In Figure A3.9, this is the rectangle that includes the following areas:

$$Total\ Revenues = B + C + E + F + H + J.$$

Producer surplus, or profits, is total revenue minus all costs. In this case, producers have two costs. One is their production costs. This is the area under their original private marginal cost curve, or area J. Their other cost is the tax. The tax per automobile is equal to the difference between $P*$ and P_0 in Figure A3.9. This tax must be paid for every automobile sold, which is $Q*$. Thus, the total tax paid is the rectangle including the following areas:

$$Tax = B + C + E + F.$$

When we subtract these two costs from total revenues, we obtain producer surplus as:

$$PS = (B + C + E + F + H + J) - J - (B + C + E + F) = H.$$

Note that producer surplus has also decreased. It used to be area (E + F + G + H), but now it is only area H.[2]

If both consumer and producer surplus have decreased, how can the tax increase social welfare? First, we need to account for the reduced pollution. With quantity reduced to $Q*$, the total externality damage is now:

$$Externality = C + F + H.$$

So, the externality damage associated with production between Q^* and Q_M, or area (D + G + I), has been avoided.

But there is another benefit to imposing the tax. The government has now collected area (B + C + E + F) in taxes. It can use this money for any socially beneficial purpose. Thus, the tax revenues represent a benefit to society as a whole.

So, to determine the net social benefits with the tax, we need to add the tax revenues to consumer and producer surplus, and subtract the new externality damages. We can now calculate the net social benefits as:

$$\textit{Net Benefits} = (A) + (H) + (B + C + E + F) - (C + F + H).$$

If we cancel out the positive and negative terms, we get:

$$\textit{Net Benefits} = A + B + E.$$

How does this compare to net benefits before the tax? Recall that benefits were previously (A + B + E – I). So benefits have increased by area I as a result of the tax. Another way of looking at this is that we have avoided the negative impacts of "too much" automobile production, represented by area I, which shows the excess of marginal costs (including external costs) over marginal benefits.

Negative Externalities—A Mathematical Approach

We can further demonstrate the welfare analysis of a negative externality by looking at a numerical example. Suppose that the demand schedule for new automobiles in the United States is given by the following equation:

$$P_d = 100 - 0.09\,Q$$

where P_d is the price of new vehicles in thousands of dollars and Q is the quantity demanded per month in hundreds of thousands.

Assume the supply schedule for automobiles is given by:

$$P_s = 4 + 0.03\,Q$$

where again P_s is the price in thousands of dollars and Q is the quantity sold per month in hundreds of thousands.

We know that at equilibrium P_d must be equal to P_s. So, we can set the two equations equal to each other to solve for the equilibrium quantity:

$$\begin{aligned} 100 - 0.09\,Q &= 4 + 0.03\,Q \\ 96 &= 0.12\,Q \\ Q &= 800 \end{aligned}$$

We can insert this quantity into either the demand or supply equation to solve for the equilibrium price. Note that we should get the same price from both equations.

$$\begin{aligned} P_d &= 100 - 0.09\,(800) \\ P_d &= 100 - 72 \\ P_d &= 28 \end{aligned}$$

or

$$P_s = 4 + 0.03\ (800)$$
$$P_s = 4 + 24$$
$$P_s = 28$$

So, the equilibrium price of new automobiles is \$28,000, and the quantity sold is 800,000 per month.[3]

We can next determine consumer and producer surplus in the automobile market. To do this, it is helpful to draw a graph of the market, as shown in Figure A3.10. Since our supply and demand curves are linear equations, both consumer and producer surplus will be the area of a triangle. For consumer surplus, we know the base of the triangle is the equilibrium quantity, or 800,000 automobiles. The height of the triangle is the difference between the equilibrium price and the intersection of the demand curve with the *y*-axis, as shown in Figure A3.10. To determine the point of intersection, we simply insert a quantity of zero in the demand curve and solve for price.

$$P_d = 100 - 0.09\ (0)$$
$$P_d = 100$$

So, the height of the consumer surplus triangle is (100 − 28), or \$72,000. Thus, total consumer surplus is:

$$CS = (\$72{,}000) * (800{,}000) * 0.5$$
$$CS = \$28.8 \text{ billion.}$$

(Note that we need to be careful with our units in this example to make sure we obtain the correct answer).

For producer surplus, the base of the triangle is again the equilibrium quantity of 800,000. To determine the height, we need to calculate the price where the supply curve intersects the *y*-axis. To do this, we insert a quantity of zero in the supply equation.

$$P_s = 4 + 0.03\ (0)$$
$$P_s = 4$$

So, the height of the producer surplus triangle is (28 − 4), or \$24,000. Producer surplus is then:

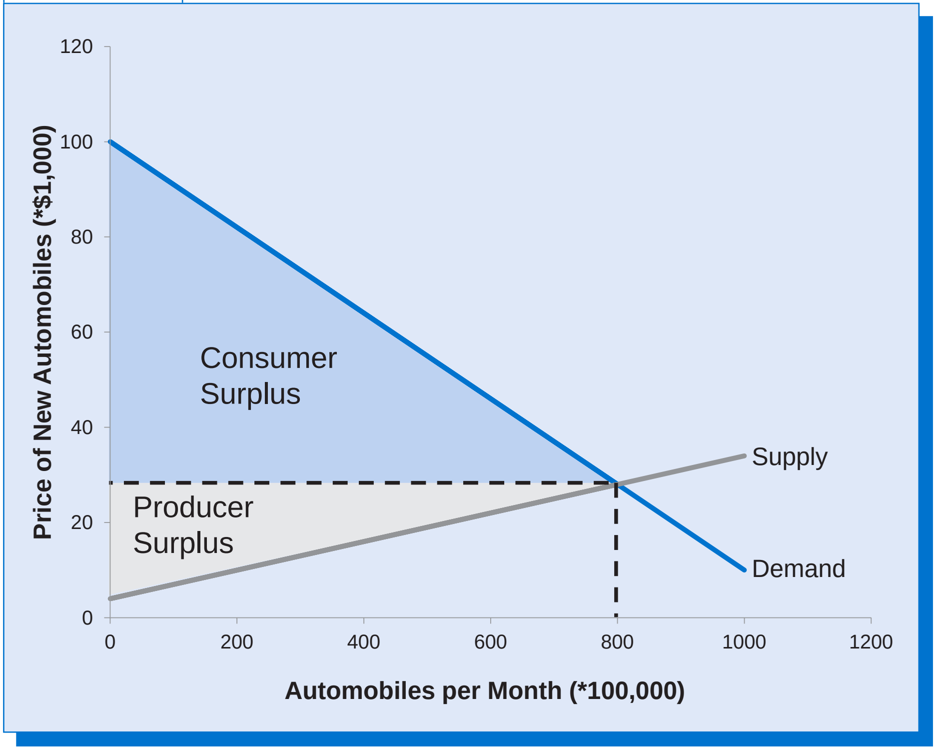
$$P_s = (\$24{,}000) * (800{,}000) * 0.5$$
$$P_s = \$9.6 \text{ billion.}$$

Total market benefits are the sum of consumer and producer surplus, or \$38.4 billion. But we also need to consider the negative external costs. Suppose that the negative external cost of each automobile is \$6,000. We can calculate the total external costs by simply multiplying this amount by the number of automobiles sold:

$$Externality = \$6{,}000 * 800{,}000$$
$$Externality = \$4.8 \text{ billion.}$$

So, the net social welfare of the automobile market would \$38.4 billion minus \$4.8 billion, or \$33.6 billion.

Figure A3.10 Automobile Market Example



Next, we consider the net social benefits if we were to institute a tax on automobiles that fully internalizes the externality. Thus, we would impose a tax of $6,000 per automobile on vehicle manufacturers. As this reflects an additional cost, the new market supply curve would shift upward by $6,000, as shown in Figure A3.11. In other words, the intercept for the supply curve with the tax would increase by 6, to:

$$P_s = (4 + 6) + 0.03\ Q$$
$$P_s = 10 + 0.03\ Q.$$

As before, we can solve for the equilibrium quantity first by setting the supply curve with the tax equal to the demand curve:

$$100 - 0.09\ Q = 10 + 0.03\ Q$$
$$90 = 0.12\ Q$$
$$Q = 750.$$

Substituting this quantity into the demand curve (we could use the new supply curve as well), we solve for the equilibrium price as:

$$P_d = 100 - 0.09\ (750)$$
$$P_d = 32.5.$$

So with the externality tax in place, the price of new vehicles increases to $32,500 and the quantity sold per month falls to 750,000.

We can calculate the new consumer surplus CS* as a triangle with a base of 750,000 and a height equal to the difference between 100 (the intercept) and the new price of 32.5, or 67.5:

$$CS^* = (\$67{,}500) * (750{,}000) * 0.5$$
$$CS^* = \$25.3125 \text{ billion.}$$

So, we can see that the tax has reduced consumer surplus by more than $3 billion.

Note that in Figure A3.11 producer surplus is the triangle above the market supply curve and below price, but we also need to deduct the tax revenue. Since the tax is $6,000, we know that the height of the producer surplus triangle is the difference between the intercept on the market supply curve ($4,000), and the new equilibrium price minus $6,000, or ($32,500 – $6,000) = $26,500. Thus the height is ($26,500 – $4,000), or $22,500. The new producer surplus is:

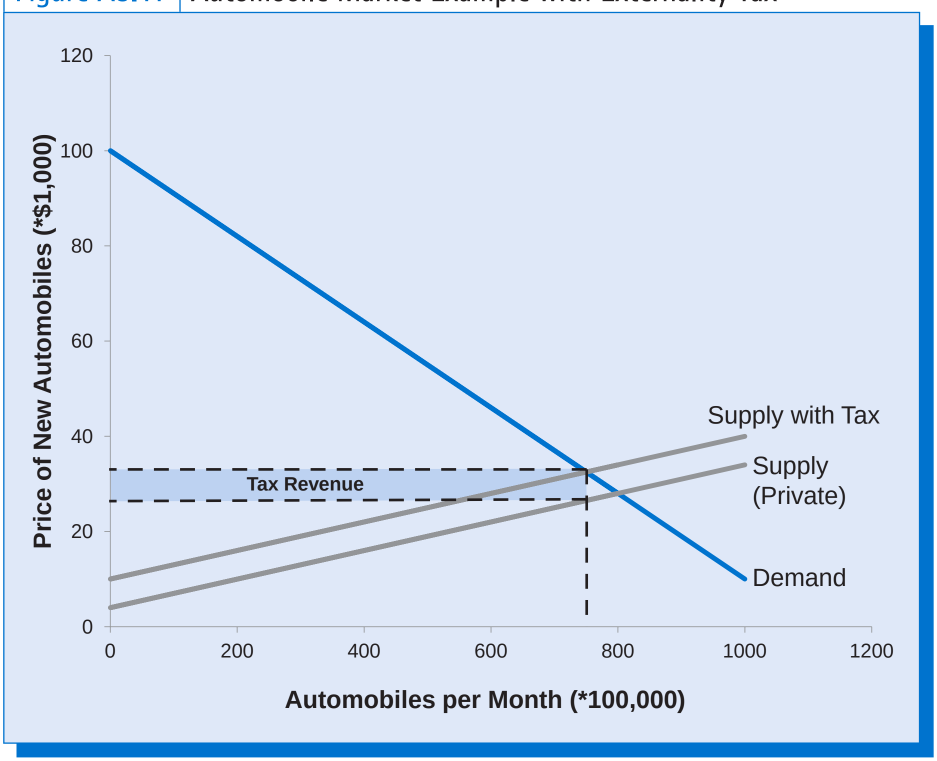
$$PS^* = (\$22{,}500) * (750{,}000) * 0.5$$
$$PS^* = \$8.4375 \text{ billion.}$$

Producer surplus has also decreased as a result of the tax, by more than $1 billion. So, the market benefits have clearly declined as a result of the tax.

Since fewer automobiles are sold, the externality damage will decrease. The damage per automobile is still $6,000, so the external costs are:

$$Externality = \$6{,}000 * 750{,}000$$
$$Externality = \$4.5 \text{ billion.}$$

Figure A3.11 Automobile Market Example with Externality Tax



So, external costs have decreased by \$300 million. Finally, we need to consider the tax revenue. The tax revenue is the \$6,000 tax multiplied by the number of vehicles sold:

$$\text{Tax Revenue} = \$6{,}000 * 750{,}000$$
$$\text{Tax Revenue} = \$4.5 \text{ billion.}$$

We see that the tax revenue is exactly equal to the remaining externality damage. In other words, the market participants are fully compensating society for the external costs of their actions. Net social welfare with the tax is:

$$\text{Net Benefits} = CS + PS - \text{external costs} + \text{tax revenues}$$
$$\text{Net Benefits} = \$25.3125 + \$8.4375 - \$4.5 + 4.5$$
$$\text{Net Benefits} = \$33.75 \text{ billion.}$$

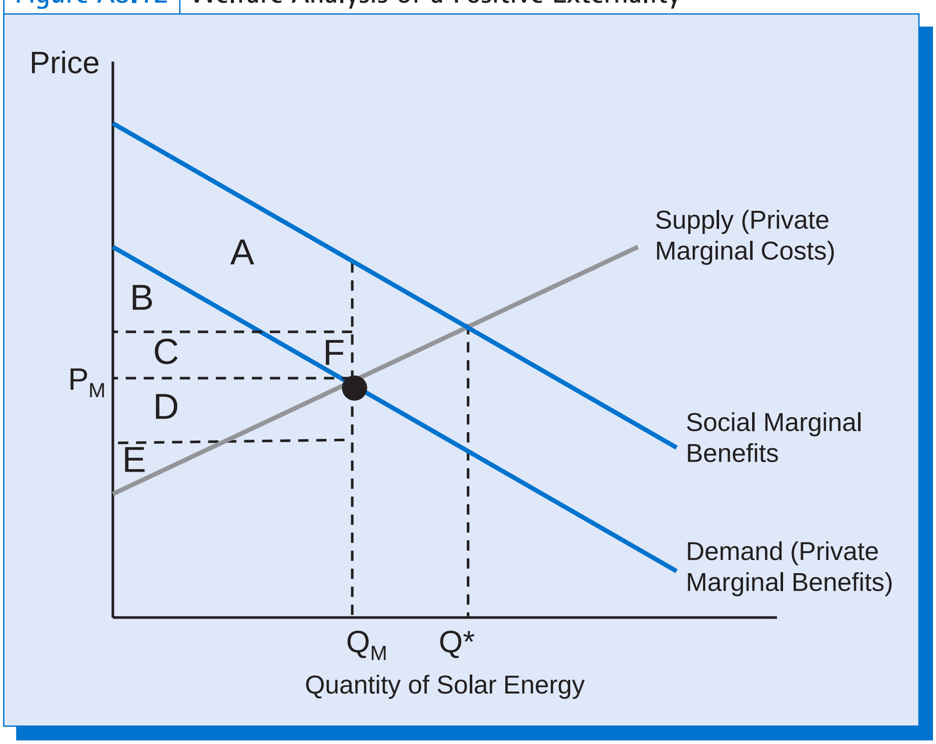
Compared to our original net welfare of \$33.6 billion, we see that net benefits have increased by \$150 million. So society is actually better off with the tax than without it.

Welfare Analysis of Positive Externalities

We now present a formal analysis of a market in the presence of positive externalities, as shown in Figure A3.12, which again shows the market for solar energy. Market benefits are the usual areas of consumer and producer surplus, with the market equilibrium price of P_M and quantity of Q_M. So, consumer surplus is:

$$CS = B + C$$

Figure A3.12 Welfare Analysis of a Positive Externality



and producer surplus is:

$$PS = D + E.$$

The area of positive externalities is the parallelogram between the two benefit curves, up to Q_M:

$$Externality = A + F.$$

So, total social benefits are simply the sum of the market and external benefits:

$$Net\ Benefits = A + B + C + D + E + F.$$

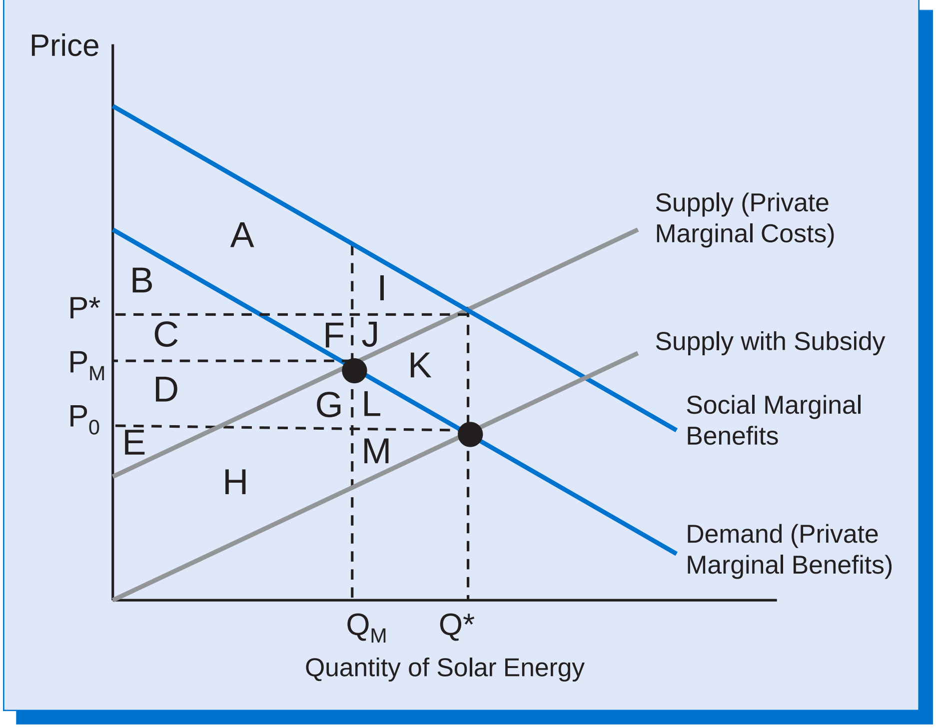
But notice in Figure A3.12 that between Q_M and Q^*, marginal social benefits exceed the marginal costs. Thus the optimal level of solar energy is Q^*, not Q_M. So, we can increase net social benefits by increasing the production of solar energy. We can do this through the use of a subsidy on the production or installation of solar systems, illustrated in Figure A3.13.

With the subsidy in place, the new equilibrium price will fall to P_0, and the quantity will increase to Q^*. Consumer surplus will be the triangle above P_0 and below the market demand curve:

$$CS = B + C + D + G + L.$$

Determining the producer surplus is a little tricky. Let's start by not considering the subsidy payment, so the cost of producing Q^* is the area under the private marginal cost curve. Note that for the first few solar panels, price is above the marginal cost curve, yielding

Figure A3.13 The Market for Solar Energy with a Subsidy



positive producer surplus of area E. But beyond this point, price is below the marginal cost curve, and solar energy producers are actually losing money. Thus, losses accrue equal to the area (G + K + L). The producer surplus without the subsidy is:

$$PS = E - G - K - L.$$

So, if the subsidy is not considered, producers appear to be losing money. But, of course, they also receive the subsidy payment. The per-panel subsidy is the vertical distance between $P*$ and P_0. Thus, the total subsidy for producing $Q*$ is:

$$Subsidy = C + D + F + G + J + K + L.$$

Net producer surplus with the subsidy is:

$$Net\ PS = (E - G - K - L) + (C + D + F + G + J + K + L)$$
$$Net\ PS = E + C + D + F + J.$$

The area that represents the positive externality is the area between the two marginal benefit curves up to $Q*$, or:

$$Externality = A + F + I + J + K.$$

Finally, we have to realize that society needs to pay for the subsidy, such as through higher taxes. So, the subsidy payment must be considered a cost from the perspective of society. The subsidy area defined above must be deducted in order to determine net social welfare. Thus net benefits are:

$$\begin{aligned} Net\ Benefits = {} & (B + C + D + G + L) + (E + C + D + F + J) + \\ & (A + F + I + J + K) - (C + D + F + G + J + K + L). \end{aligned}$$

If we cancel out the positive and negative terms, we are left with:

$$Net\ Benefits = A + B + C + D + E + F + I + J.$$

Comparing this to the estimate of net benefits without a subsidy, we can see that the net gain in social welfare as a result of the subsidy is (I + J). Once again, society is better off with market intervention than without it. The subsidy moves us to the efficient outcome.

Key Terms and Concepts from Appendices

consumer surplus

economies of scale

law of demand

law of supply

marginal costs

market equilibrium

price elasticity of demand

price elasticity of supply

producer surplus

shortage

surplus

willingness to pay

Notes

1. Economists generally describe demand curves as shifting to "the right" or "the left," not up or down. This is because it makes more intuitive sense to say that at a given price consumers will demand more or less than to say that consumers will purchase a given quantity at a higher or lower price.
2. Note that producer surplus can also be measured as the difference between price and the supply curve with the tax. This would be area (B + E). Since the two supply curves are parallel, this is the same as area H.
3. These values are relatively close to actual new monthly automobile sales in the United States and the average price of a new vehicle.

CHAPTER 4

Common Property Resources and Public Goods

Chapter 4 Focus Questions

- Why are resources like fisheries and groundwater often damaged through excessive use?
- What policies are effective for managing open-access resources?
- How should we preserve public goods like National Parks, oceans, and the atmosphere?

4.1 COMMON PROPERTY, OPEN ACCESS, AND PROPERTY RIGHTS

As we saw in Chapter 3, clearly defined property rights can potentially be used for efficient resource allocation, even in the presence of externalities. In market economies, private property rights are central. This has not always been the case. In traditional or tribal societies, private property rights over resources are rare. Resources important to the life of the tribe are either held in common (like a common grazing ground) or are not owned at all (like animals that are hunted for food). Economically developed societies—we like to think of ourselves as "advanced" societies—have generally evolved elaborate systems of property rights covering most resources as well as most goods and services. But modern industrialized countries also have resources, goods, and services, which are difficult to categorize as property.

A free-flowing river is one example. If we think of the river simply as a quantity of water that flows past people's land, we can devise rules for "ownership" of the water, allowing a certain amount of water withdrawal per landowner. But what about the aquatic life of the river? What about the use of the river for recreation: canoeing, swimming, and fishing? What about the scenic beauty of the riverside?

Some of these aspects of the river might also become specific types of property. For example, in Scotland trout-fishing rights on certain rivers are jealously guarded property. But it is difficult to parcel up every function of the river and define it as someone's property. To some degree, the river is a **common property resource**—it is accessible to everyone and not subject to private ownership. Technically speaking, a common property resource is a **nonexcludable good** because people cannot easily be excluded from using it. The other characteristic of a common property resource is that it is a **rival good**, meaning that its use by one person diminishes the quantity or quality of the resource available to others.

common property resource a resource that is available to everyone (nonexcludable), but use of the resource may diminish the quantity or quality available to others (rival).

nonexcludable good a good that is available to all users, under conditions in which it is impossible, or at least difficult, to exclude potential users.

rival good a good whose use by one person diminishes the quantity or quality of the good available to others.

Consider groundwater as an example of a common property resource. Anyone can access groundwater by drilling a well; thus, it is nonexcludable. But groundwater is rival because each user depletes the aquifer somewhat, leaving less water available to other potential users.

How can a common property resource be managed to maximize social benefits? Is government regulation required to prevent the overuse of the resource, and, if so, what types of regulations can be effective? We address these questions using the example of an ocean fishery.

The Economics of a Fishery

A classic example of a common property resource is an ocean fishery. While inland and coastal fisheries are often governed by private, traditional, or government management systems, fisheries in the open ocean are typically **open-access resources**. An open-access resource is a common property resource that lacks any system of rules governing its use. Anyone who wants to can fish in nonterritorial waters, which means that no one owns the basic resource, the wild stock of fish. We use this example to apply some of the basic concepts of production theory to an open-access resource.

open-access resource(s) a resource that offers unrestricted and unregulated access such as an ocean fishery or the atmosphere.

How can we apply economic theory to a fishery? Let's start with common sense. If only a few fishing boats start operations in a rich fishery, their catch will certainly be good. This is likely to attract other fishers, and as more boats join the fishing fleet the total catch will increase.

As the number of fishing boats becomes very large, it is clear that the capacity of the fishery will be strained, and the catch of individual boats will diminish. We know from experience that if this process is taken too far, the output of the whole fishery can be badly damaged. At what point does it become counterproductive to put in more effort, in terms of more boat trips? Which forces can drive us past that point? Economic theory can give us some insights into these critical questions of common property resource management.

We can envision the fishery's **total product** as shown in Figure 4.1. The horizontal axis shows fishing effort, measured in number of boat trips. The vertical axis shows the total catch of all the boats, measured in tons of fish caught. As the number of boat trips increases, the total product curve shown in Figure 4.1 goes through three distinct phases.

The first is a period of **constant returns to scale** (here shown from 0 to 400 boats). In this range, each extra boat finds an ample supply of fish and is able to return to port with a catch of 10 tons. For simplicity, we assume that all boats are the same in this example. Thus each boat catches the same amount of fish. During the period of constant returns to scale, the fishery is not subject to rivalry, as each additional fisher does not reduce the quantity of fish that can be caught by other fishers.

The second phase is a period of **diminishing returns** to effort, shown from 400 to approximately 850 boats. It is now becoming more difficult to catch a limited number of fish. When an extra boat puts out to sea, it increases the total catch of the fishery, but it also reduces by a small amount the catch of all the other boats. The natural resource is no longer ample for all; now there is intense competition for fish stocks, which makes the job tougher for all fishers. In other words, the resource has now become rival.

Finally, there is a period of **absolutely diminishing returns**, above 850 boats, a situation in which having more boats actually *decreases* the total catch. Here it is evident that **overfishing** is taking place. Stocks of fish are being depleted. The fish population's ability to replenish itself is damaged, and we have the makings of both an economic and an ecological collapse.[1]

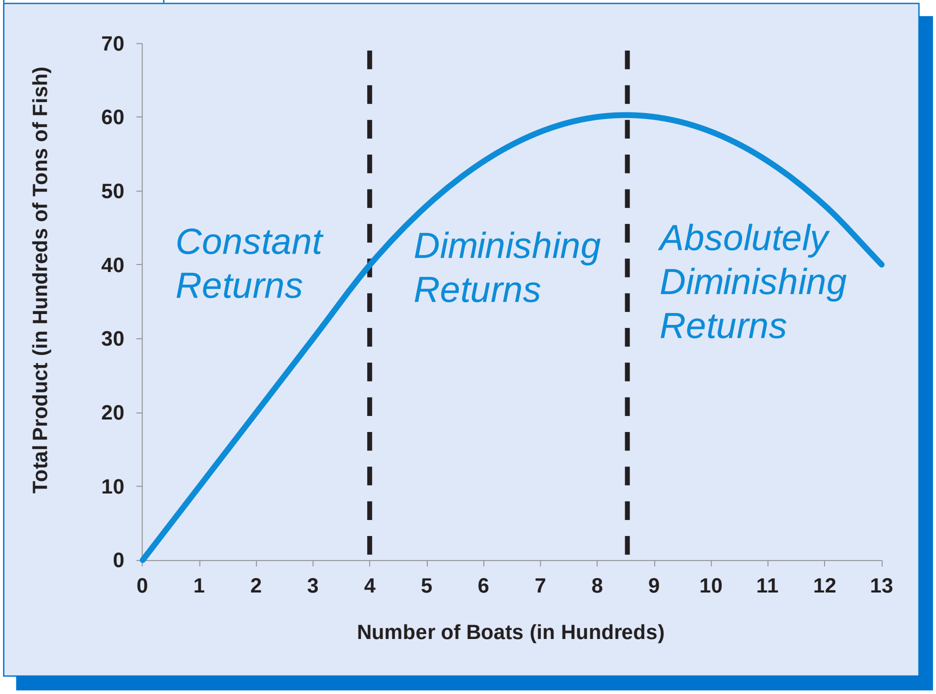
> **total product** the total quantity of a good or service produced with a given quantity of inputs.
>
> **constant returns to scale** a proportional increase (or decrease) in one or more inputs results in the same proportional increase (or decrease) in output.
>
> **diminishing returns** a proportional increase (or decrease) in one or more inputs results in a smaller proportional increase (or decrease) in output.
>
> **absolutely diminishing returns** an increase in one or more inputs results in a decrease in output.
>
> **overfishing** a level of fishing effort that depletes the stock of a fishery over time.

To understand the economic forces motivating the fishers, we must consider how different levels of total fishing effort affect their profits. We assume that fishers are interested only in making profits for themselves. The first step in determining profits is to convert the quantitative measure of tons of fish landed into a monetary figure showing total revenue earned. This can be done by simply multiplying the quantity of fish by the price per ton ($TR = P*Q$). We assume here that the price of fish is stable at $1,000 per ton. We are implicitly assuming that this fishery is small enough relative to the total market that its output does not significantly affect the market price. If this fishery were the only source of fish for the market, we would have to consider price changes also.

We can now calculate the **total revenue** of the fishery, as shown in Table 4.1. Next, let's assume that cost of operating a fishing boat

> **total revenue** the total revenue obtained by selling a particular quantity of a good or service; equal to price per unit multiplied by quantity sold.

Figure 4.1 Total Product of the Fishery



marginal costs the cost of producing or consuming one more unit of a good or service.

average cost the average cost of producing each unit of a good or service; equal to total cost divided by the quantity produced.

total cost the total cost to a firm of producing its output.

profits total revenue received minus total cost to producers.

is constant at $4,000 per boat. Thus the **marginal cost** of a boat (i.e., the cost of sending one more boat into the fishery) is always $4,000. Again, all boats are the same in this example, so the cost of operating each boat is assumed to be the same. Since the cost of operating a boat is constant, the **average cost** of operating a boat is also always $4,000. The **total cost** for all boats in the fishery is equal to $4,000 multiplied by the number of boats. By subtracting the total revenue in the fishery from the total cost (TC) of operating the boats, we can obtain the **profits** ($TR - TC$) of the fishery, shown in Table 4.1.

We can see from Table 4.1 that total profits in the fishery are $3 million at both 600 and 700 boats. Figure 4.2 charts the total revenue, costs, and profits of the fishery at each effort level. We see that total fishery profits are maximized between 600 and 700 boats, or at approximately 650 boats. If fishing effort is too high (more than 1,200 boats), total profits of the fishery actually become negative.

Incentives for Overfishing

We know that the profit-maximizing level of effort, considering the entire fishery, is 650 boats. But in the absence of any regulations governing how the fishery is managed, what level of fishing effort will occur? We assume that each fisher is only concerned with his or her profits. Thus individuals will not consider how their activities affect the fishery as a whole, only whether fishing is profitable to them. So rather than looking at the values in Table 4.1 for the total fishery, we need to consider the perspective of the individual fisher.

Table 4.1 Total Fish Catch, Revenue, Costs, and Profit

Number of boats	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300
Total fish catch (hundred tons)	10	20	30	40	48	54	58	60	60	58	54	48	40
Total revenue (in million $)	1.0	2.0	3.0	4.0	4.8	5.4	5.8	6.0	6.0	5.8	5.4	4.8	4.0
Total costs (in million $)	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6	4.0	4.4	4.8	5.2
Total profits (in million $)	0.6	1.2	1.8	2.4	2.8	3.0	3.0	2.8	2.4	1.8	1.0	0.0	−1.2

average revenue the average price a firm receives for each unit of a good or service; equal to total revenue divided by the quantity produced.

We know that each boat costs \$4,000 to operate. For each level of effort in Table 4.1, we can calculate the revenue for each fisher as the total revenue in the fishery divided by the number of boats. For example, with 800 boats operating total revenue is \$6 million, and thus the revenue per boat is \$7,500 (\$6,000,000/800). This is the **average revenue** or revenue per boat, as shown in Table 4.2. In mathematical terms, $AR = TR/Q$. By subtracting the cost per boat of \$4,000, we obtain the profit per boat, also shown in Table 4.2.

Suppose that 400 boats are operating. We see in Table 4.2 that each boat is bringing in revenues of \$10,000, yielding an individual profit of \$6,000. Other people will notice that fishing is rather profitable, and thus new fishers will be attracted to enter the fishery. So long as fishers have free entry to the industry, the number of boats will continue to increase. Either existing fishers will acquire more boats, or new operators will enter the fishery.

Once we exceed 400 boats, in Table 4.2 profits per boat begin to decline as we enter the region of diminishing returns. But as long as operating each boat is profitable, there is an incentive for more boats to enter the industry—even into the region of absolutely diminishing returns. For example, when 1,000 boats are operating, the profits per boat are still \$1,800. So even though additional boats actually reduce the total catch, and total revenue, of the fishery, there is still an economic incentive for individual fishers to send more boats into the fishery.

open-access equilibrium the level of use of an open-access resource that results from a market with unrestricted entry; this level of use may lead to depletion of the resource.

Only when we reach 1,200 boats do profits per boat finally fall to 0. If any more boats operate above 1,200, then profits per boat actually fall below 0 (i.e., every boat is losing money), and there would be an incentive for some fishers to leave the industry. Above 1,200 boats, the market is sending a "signal," through unprofitability, that the industry is overcrowded. Thus the **open-access equilibrium**

Figure 4.2 Total Revenue, Costs, and Profits for the Entire Fishery

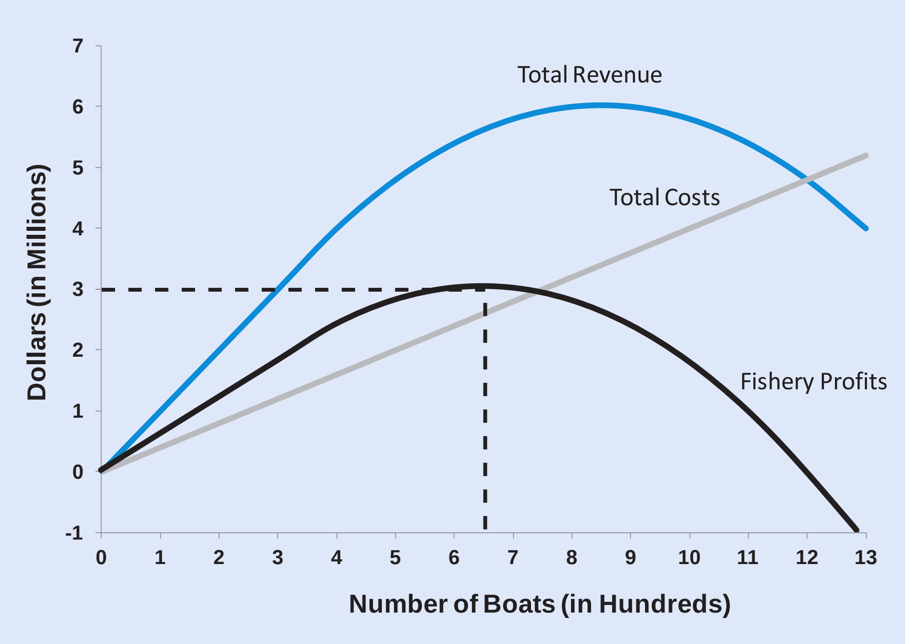


Table 4.2 Revenue, Costs, and Profits for Individual Fishers

Number of boats	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300
Revenue per boat (in thousand $)	10.0	10.0	10.0	10.0	9.6	9.0	8.2	7.5	6.6	5.8	4.9	4.0	3.1
Cost per boat (in thousand $)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Profit per boat (in thousand $)	6.0	6.0	6.0	6.0	5.6	5.0	4.2	3.5	2.6	1.8	0.9	0.0	–0.9

is 1,200 boats, which is the point at which there is no further incentive for entry to or exit from the market.[2]

The open-access equilibrium is clearly not economically efficient. A formerly profitable industry has become unprofitable, and total fish catch has fallen, reducing overall social benefits. The market signal that the industry is overcrowded comes far too late—well above the profit-maximizing level of 650 boats. Looking at Table 4.1, we see that total profits in the industry at 1,200 boats are 0. Industry profits can actually be increased by *reducing* fishing effort.

In addition to being economically inefficient, the open-access equilibrium is also not ecologically sustainable. As the open-access equilibrium is in the region of absolutely diminishing returns, eventual collapse of the fishery is a likely outcome. The forces of free entry and profit maximization at the individual level, which usually work to promote economic efficiency, have exactly the opposite effect in the case of a common property resource. These forces encourage overfishing, which ultimately eliminates any profitability in the industry and destroys the natural resource. The economic explanation is that fishers have free access to a valuable resource—fish stocks. Economic logic tells us that an underpriced resource will be overused, and a resource priced at zero will be squandered.

This phenomenon is sometimes referred to as the **tragedy of the commons**.[3] Because common property resources belong to no one in particular, no one has an incentive to conserve them. On the contrary, the incentive is to use as much as you can before someone else gets it. When resources are ample, as in precolonial America when the stocks of fish were far beyond the needs or fishing abilities of the small population, there is no problem. When the population and demand are large enough, and fishing technologies more sophisticated, the economic logic that we have sketched out leads to a critical danger of overfishing and even complete collapse of the fishery.

tragedy of the commons the tendency for common property resources to be overexploited because no one has an incentive to conserve the resource while individual financial incentives promote expanded exploitation.

Marginal Analysis of a Common Property Resource

Economists seeking to determine efficient outcomes focus on comparing **marginal benefits** and marginal costs. This is really just common sense—if the benefits of doing something exceed the costs, then it normally makes sense to do it. So in our fishing example, as long as the benefits of one more boat exceed the costs of one more boat, then it makes sense for the industry as a whole to keep increasing the number of boats. In other words, if the **marginal revenue** of a boat exceeds the marginal cost, it is efficient to increase the number of boats, which will have the effect of increasing total industry profits. However, when the marginal costs equal or exceed the marginal revenue, we should stop adding boats, which would decrease total industry profits. Thus the economically efficient outcome occurs where marginal revenue equals marginal cost. Note that in this example we define efficiency in terms of only industry profits—we are not considering consumer benefits or externalities.

marginal benefit the benefit of producing or consuming one more unit of a good or service.

marginal revenue the additional revenue obtained by selling one more unit of a good or service.

We know the marginal cost per boat is constant at $4,000. To calculate the marginal revenue for each level of fishing effort, we calculate the additional revenue for each change in effort (effort being measured by the number of boats). We normally speak of the marginal change from one level of effort to another; thus, we would calculate the marginal revenue *between* two levels of effort.

Table 4.3 Marginal Revenue and Cost Analysis of Fishery

Number of boats	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300
Total revenue (in $ million)	0.0	1.0	2.0	3.0	4.0	4.8	5.4	5.8	6.0	6.0	5.8	5.4	4.8	4.0
Marginal revenue per boat (in $ 000)		10	10	10	10	8	6	4	2	0	–2	–4	–6	–8
Marginal cost per boat (in $ 000)		4	4	4	4	4	4	4	4	4	4	4	4	4

Let's consider the marginal revenue that results from increasing the number of boats from 400 to 500. Total revenue in the industry increases from \$4 million to \$4.8 million, an increase of \$800,000. Since an additional 100 boats increases revenues by \$800,000, the marginal revenue per boat when the number of boats increases from 400 to 500 is \$800,000/100 = \$8,000.[4] Expressed mathematically, $MR = \Delta TR/\Delta Q$.

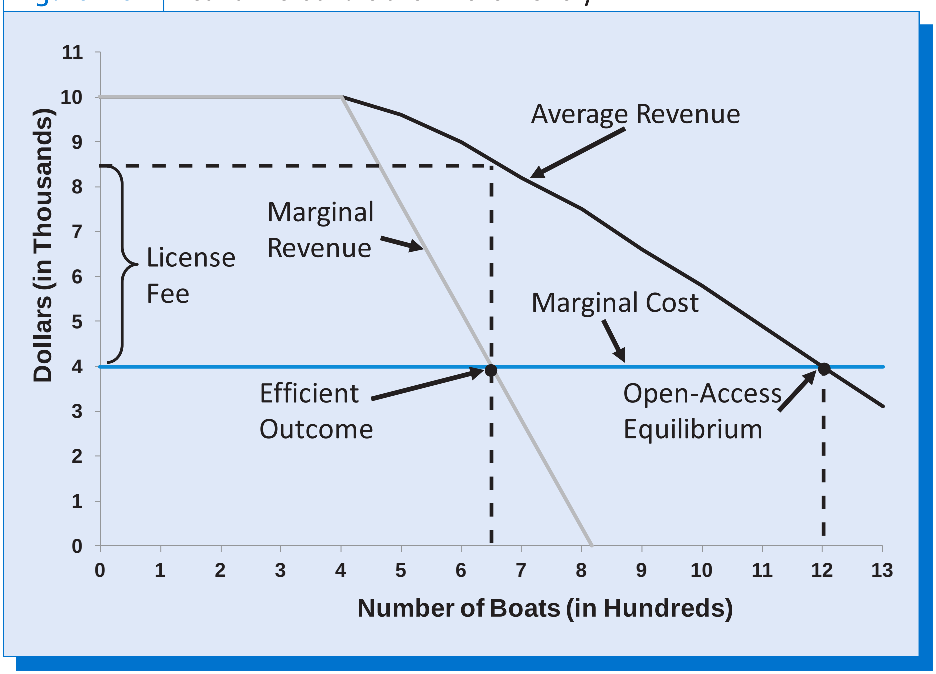
It makes economic sense to increase from 400 to 500 boats, because marginal cost is \$4,000 per boat. In other words, marginal revenue exceeds marginal cost, so raising the number of boats from 400 to 500 increases overall profits in the fishery.

Table 4.3 calculates the marginal revenue per boat between each effort level, along with the marginal cost. Between 600 and 700 boats, the marginal revenue is exactly equal to the marginal cost of \$4,000 per boat. So we can conclude that the efficient level of effort is between 600 and 700 boats, as illustrated in Figure 4.3.

The efficient outcome is where marginal revenue equals marginal cost, at approximately 650 boats. But the open-access equilibrium occurs where *average* revenue equals marginal cost (the cost of an additional boat). This occurs at 1,200 boats. In this example, due to our assumption of constant marginal costs, the marginal cost of \$4,000 per boat is also the average cost (i.e., the cost for each boat owner). Note that the difference between average revenue and average cost at 650 boats is about \$4,600 in Figure 4.3. This represents the profit that each boat makes at the efficient level of effort. We will see why this is important in the next section. If 650 boats each obtain a profit of about \$4,600, then total industry profits are maximized at \$3 million. Obviously this represents a big improvement over total profits at the open-access equilibrium, which are zero with 1,200 boats operating.

The efficient outcome is also more likely to be ecologically sustainable. Referring back to Figure 4.1, we see that at 650 boats we are in the region of diminishing returns, rather than the area of absolutely diminishing returns. While fishing effort is high enough to cause some reduction in individual yields, it is unlikely to cause collapse of the fishery.

Figure 4.3 Economic Conditions in the Fishery



Economic Policies for Fishery Management

What policies might be used to achieve the efficient outcome, as well as protecting the fishery by reducing effort? One option may be for all the fishers to agree voluntarily to limit fishing effort to 650 boats. But the problem is that each fisher will still have a strong economic incentive to send one more boat out, which may cause the agreement to break down. Also, new fishers will be enticed to enter the fishery and would not be bound by the voluntary agreement.

As with the problem of externalities, achieving the efficient outcome requires government intervention. One policy option is to use a **license fee** to discourage overfishing. The correct fee can be determined by referring to Figure 4.3. We want fishing to be profitable up to the efficient level of 650 boats, but we want to discourage fishing beyond this level. So the fee needs to be high enough to make the 651st boat unprofitable, but still allow the 650th to be profitable. At 650 boats, average revenue is $8,600 per boat, and profits are $4,600 per boat. The potential profit per boat at 651 boats would be slightly less than $4,600. So if we charge a license fee of $4,600, then the 651st boat would be unprofitable, and fishing effort would reach a new equilibrium at 650 boats. In other words, even with a license fee of $4,600 per boat, fishing remains profitable up to 650 boats, but then becomes unprofitable above 650 boats. Thus the "correct" license fee is the difference between average revenue and average cost at the efficient level of effort. The license fee effectively moves us from the inefficient open-access equilibrium to the efficient outcome. The $3 million difference between total costs and total revenues is now, however, collected by the government as fees, rather than going to the industry participants as profits.

license fee the fee paid for access to a resource, such as a fishing license.

At 650 boats, each fisher will now be in the position of a perfect competitor, making a minimal or "normal" profit.[5] But with the license fee in effect, the logic of competition now works to protect the ecosystem, not to destroy it. In effect, fishers will be charged a fee for the use of a previously free resource—access to fish stocks. The government acts as a "landlord," charging a "rent" for access to the ocean. This policy might be politically unpopular in fishing communities, but it will prevent the industry from destroying the means of its own livelihood.

By charging $4,600 per boat, the government effectively collects the potential industry economic profits of $3 million. From a social point of view, this can be justified by observing that the ocean "belongs" to all of us—but of course it is important that these revenues be used wisely. Fee revenue could be used, for example, to improve the habitat of the fishery, to compensate those who are forced out of the fishery when the fee is imposed, or to invest in technologies that reduce fishery damage.

Another policy to achieve the same goal would be the use of a **quota**, or catch limit. Government officials can determine a quota for the entire fishery, but determining who receives the rights to a limited fish catch can become controversial. If the right is allocated to current fishers, new entrants will be barred from the industry. Alternatively, fishers might receive **individual transferable quotas (ITQs)**, which could be sold to someone entering the business. In some cases, limited rights to hunt or fish certain species are allocated to indigenous peoples. Aleut people, for example, have the right to hunt a limited number of endangered bowhead whales (See Box 4.1 for another example of ITQs in practice). An advantage of the ITQ system, from the point of view of the fishers, is that the revenues from the fishery remain with the fishers who hold the ITQs, rather than being collected by the government as in the case of a license fee.

quota/quota system a system of limiting access to a resource through restrictions on the permissible harvest of the resource.

individual transferable quotas (ITQs) tradable rights to harvest a resource, such as a permit to harvest a particular quantity of fish.

Box 4.1 COMMON-PROPERTY RESOURCE MANAGEMENT IN PRACTICE: INDIVIDUAL TRANSFERABLE QUOTAS

Iceland has one of the most extensive systems of individual transferable quotas for its marine fisheries. In 1990 Iceland passed the Fisheries Management Act, which established ITQs for all fisheries, with permits allocated to each fishing vessel based on its proportional share of the national catch during a baseline period. Each year the total allowable catch is determined based on the current scientific evidence regarding the health of each fishery. For example, the allowable cod catch each year is set equal to 20 percent of the "catchable biomass" of the stock. As the health of the cod fishery has improved, the allowable catch has increased—from 130,000 tons in 2007 to about 230,000 tons in 2015.

The ITQs are fully tradable, and even divisible into smaller shares if a fisher wishes to only transfer part of his or her total allocation. Iceland has also implemented regulations that prohibit one company from obtaining an excessive proportion of the permits for a fishery. For example, one company cannot have the rights to more than 12 percent of the national cod allowable catch, or 20 percent of the halibut catch. A separate quota system is in place specifically for smaller boats, to allow the coexistence of both small- and large-scale fishing operations.

According to Sigurdur Ingi Johannsson, the Minister of Fisheries and Agriculture, the ITQ system has been very successful. In 2015 he stated that the approach has both improved the health of Iceland's fisheries and led to an increase in fishery revenues. He said, "We need to use responsible, science-based analysis, but I would say it's a case of so far, so good. Cod, our most valuable fish-stock, is stronger than it has been for 50 years. We are also using fewer vessels, too, which is having less of an environmental impact."

Sources: Davies, 2015; Icelandic Ministry of Fisheries and Agriculture web site, http://www.fisheries.is/management/fisheries-management/individual-transferable-quotas/.

Yet another possibility is for the government to sell fishing quota rights at auction, which will lead to an economic result similar to that for the license fee. Suppose that the government correctly determines that 650 is the efficient quantity of boats and makes this number of permits available in an auction. What would be the ultimate bidding price for these permits? If fishers can correctly estimate that potential economic profits at this effort level are $4,600 per boat (average revenue minus average cost), then the permit price would get bid up to $4,600. In essence, the quota produces the same outcome as the license fee, both in terms of the number of boats and government revenue of $3 million. Whichever method is chosen, it requires a consciously planned government intervention. Although economists often argue that markets operate more efficiently without government intervention, here is a case in which government intervention is *required* to achieve an economically efficient (and ecologically sustainable) solution.[6]

Managing Common Property Resources

We have not considered externalities yet in our analysis. It may be that high levels of fishing effort cause negative externalities, such as water pollution or reduced recreational opportunities. If this were the case, then the socially efficient outcome might be less than 650 boats, and we would also need to take these externalities into account when setting the license fee or the quota. If we could monetize the externality damage, we would add this amount to the fee to further reduce effort.

The need for social regulation to manage common-property resources has been well recognized throughout history. Many traditional societies have maintained flourishing fisheries through the implementation of socially accepted rules governing fishing activity. This approach reflects a longstanding principle of limited catch and conservation of resources.

Population growth, high demand, and advanced technology have complicated the implementation of such sound principles. As demand for fish increases globally, and more areas become overfished, the price of fish will tend to rise. A higher price will make the problems of open access worse, since it increases the profitability of fishing and encourages more entry. Improved technology also worsens the problem of overfishing. Usually increased productivity is good for society, but in the case of an open access resource, it hastens the pressure on the resource and makes ecosystem collapse more likely. For example, sonar systems that enable tracking of fish make it easier for large fishing boats to increase their catch—but also accelerate the depletion of fish stocks.

The economic policies of license fees and ITQs discussed above are not the only potential approaches for preventing the exploitation of common property resources. One alternative is to privatize such resources, based on the perspective that private owners will have an incentive to manage them sustainably. But as we'll see in Chapter 19 when we discuss the economics of forest management, private ownership of a natural resource doesn't necessarily ensure environmentally sustainable management. In particular, an owner of a forest, or of a private fishery, may still have an economic incentive to overexploit the resource.

An alternative to policies such as ITQs and private ownership is the potential for users of a common property resource to devise their own agreement to prevent the tragedy of the commons. Elinor Ostrom won the Nobel Prize in Economics in 2009 for her pioneering research on the ways different societies have addressed the management of common property resources.[7] She identified many instances where resource users were able to work out a cooperative strategy for effective and sustainable management without the need for government regulation or privatization. She found that local users often hold important knowledge that may not be available to government officials when setting allowable harvest levels. Also, she discovered that local users are likely to be quite aware that individual financial self-interest in the short term can lead to ecological and economic collapse in the long run, and thus take preemptive steps.

Ostrom ultimately identified the conditions under which cooperative local management of a common property resource can be effective. Among the conditions she recognized are:

- Most users of a resource should be involved in devising rules for managing the resource.
- There should be monitors of the resource, accountable to the resource users, who periodically evaluate conditions.
- There should be mechanisms to resolve conflicts that are responsive and low-cost.
- Rules for managing the resource should be adapted to local conditions.
- There should be graduated sanctions for resource users who violate the rules.

We should also note that Ostrom's framework is not necessarily incompatible with government involvement. She notes that for large-scale common property resources a "nested" approach may be needed, involving organizations at different levels. For example, a state or federal government might be needed to administer and enforce an ITQ system, but a local group of fishers might be integral in designing the system and handling disputes. Thus a broader lesson is that effective management of natural resources is often based on a participatory approach that incorporates diverse viewpoints, including local (possibly indigenous) knowledge, history, and culture. Effective management of common property resources that are national or global in scale will clearly require government involvement (as we'll discuss at the end of this chapter), but should still be mindful of varying local contexts.

4.2 THE ENVIRONMENT AS A PUBLIC GOOD

public goods goods that are available to all (nonexcludable) and whose use by one person does not reduce their availability to others (nonrival).

nonrival good a good whose use by one person does not limit its use by others; one of the two characteristics of public goods.

free riders an individual or group that obtains a benefit from a public good without having to pay for it.

We now consider the economics of **public goods**. Like common property resources, public goods are nonexcludable, meaning that they are available to everyone. But while common property resources are rival, public goods are **nonrival**. If a good is nonrival, its use by one person does not reduce its availability or quality to others.[8]

One example is the National Park system of the United States. National Parks are open to all, and (except where overcrowding becomes a significant problem) their use by some people does not reduce others' ability to enjoy them. Public goods are not necessarily environmental in character: The highway system and national defense are often cited as examples of public goods. Another nonenvironmental example is public radio, because anyone with a radio can listen to it and additional people listening to public radio do not reduce its availability to others. Many aspects of environmental preservation, however, do fall into the public goods category, since virtually everyone has an interest in a sound and healthy environment.[9]

Can we rely upon private markets to provide us with the appropriate level of public goods? The answer is clearly no. In many cases, private markets will not provide public goods at all. With market goods, the ability to charge a price, along with recognition of property rights, acts as a means to exclude nonbuyers from the benefits that buyers enjoy. Because of the nonexcludable and nonrival characteristics of public goods, no individual consumer has an incentive to pay for something that everyone else can freely enjoy.

A second possibility is to rely on donations to supply public goods. This is done with some public goods, such as public radio and television. Also, some environmental groups conserve habitats that, while privately owned, can be considered public goods (see Box 4.2). Donations, however, generally will not raise sufficient funds for an efficient provision of public goods. Since public goods are nonexcludable, each person can receive the benefits of public goods regardless of whether they pay. So while some people may be willing to donate money to public radio, many others simply listen to it without paying anything. Those who do not pay choose to be **free riders**. It is obvious that a voluntary donation system would not work for, say, the provision of national defense or the highway system.

Although we cannot rely upon private markets or voluntary donations to supply public goods, their adequate supply is of crucial interest to the whole society. Once again, the solution to the dilemma requires some degree of government involvement. Decisions regarding the provision of public goods are commonly decided in the political arena. This is generally true of, for example, national defense. A political decision must be made, taking into account that some citizens may favor more defense spending, others less. But a decision must be made, and after the decision is made, we all pay a share of the cost through taxes.

Similarly, decisions on the provision of environmental public goods have to be made through the political system. Congress, for example, must decide on funding for the National

Box 4.2
THE NATURE CONSERVANCY

While voluntary donations cannot be relied on to provide an efficient level of public goods, voluntary efforts can effectively supplement government efforts. A successful example is The Nature Conservancy, an environmental group founded in 1951. Rather than focusing on political lobbying or advertising, The Nature Conservancy directs most its efforts toward purchasing land with the donations that it receives. This approach essentially creates a voluntary market in which people can express their preference for habitat conservation.

The organization started in the United States and now operates in more than 30 countries. The Nature Conservancy has protected over 119 million acres globally—an area equal in size to the U.S. state of New Mexico. Most of its protected areas are open for recreation, although it also allows logging, hunting, and other extractive uses on some properties.

In addition to directly purchasing and managing land, The Nature Conservancy also works with landowners to establish *conservation easements*. In a conservation easement agreement, a landowner sells the rights to develop his or her land in certain ways (e.g., creating a housing subdivision), while still retaining ownership and continuing with traditional uses such as ranching and timber harvesting. Other efforts include their "Plant a Billion Trees" campaign to plant trees in the tropical rainforest of Brazil. Each $1 donated is used to plant one tree.

The Nature Conservancy's nonconfrontational, pragmatic approach is widely respected and generally considered effective. It is normally ranked as one of the most trusted nonprofit organizations and is praised for its efficient use of donations. While some environmentalists are critical of some of its policies, for example, selling parcels of donated land for a profit rather than conserving them, its efforts provide a means for individuals to use the market to promote habitat conservation.

Source: The Nature Conservancy, www.nature.org.

Park system.[10] Will more land be acquired for parks? Might some existing park areas be sold or leased for development? In making decisions like this, we need some indication of the level of public demand for environmental amenities. Can economic theory be of any help here?

Economics of Public Goods

The problem of public good provision cannot be solved through the ordinary market process of supply and demand. In the fishery example discussed above, the problem lay on the production side—the ordinary market logic led to overexpansion of production and excessive pressure on resources. In the case of public goods, the problem is on the demand side. Recall that in Chapter 3 we referred to a demand curve as both a marginal benefit curve and a willingness-to-pay curve. A consumer is willing to pay, say, up to $30 for a shirt because that is his or her perceived benefits from owning the shirt. But in the case of a public good, the marginal benefits that someone obtains from a public good are not the same as their willingness to pay for it. In particular, their willingness to pay is likely to be significantly lower than their marginal benefits.

A simple example illustrates this point. Consider a society with just two individuals: Doug and Sasha. Both individuals value forest preservation—a public good. Figure 4.4 shows the marginal benefits each person receives from the preservation of forest land. As with a regular demand curve, the marginal benefits of each acre preserved decline with more preservation.

We see that Doug receives greater marginal benefits than Sasha does. This may be because Doug obtains more recreational use of forests, or it may simply reflect different preferences.

vertical addition adding the price of more than one demand curve at the same quantity demanded.

The aggregate, or social, marginal benefits from preserved forest land are obtained by the **vertical addition** of the two marginal benefit curves. In the top graph in Figure 4.4, we see that Doug receives a marginal benefit of $5 for an additional acre of forest preservation if 10 acres are already preserved. Sasha receives a marginal benefit of only $2. So the aggregate benefits of an additional acre of preserved forest are $7, as shown in the bottom graph. Note that the aggregate curve is kinked because to the right of the kink the curve only reflects Doug's marginal benefits, since Sasha's marginal benefits are zero in this range.

social benefits the market and nonmarket benefits associated with a good or service aggregated across all members of a society.

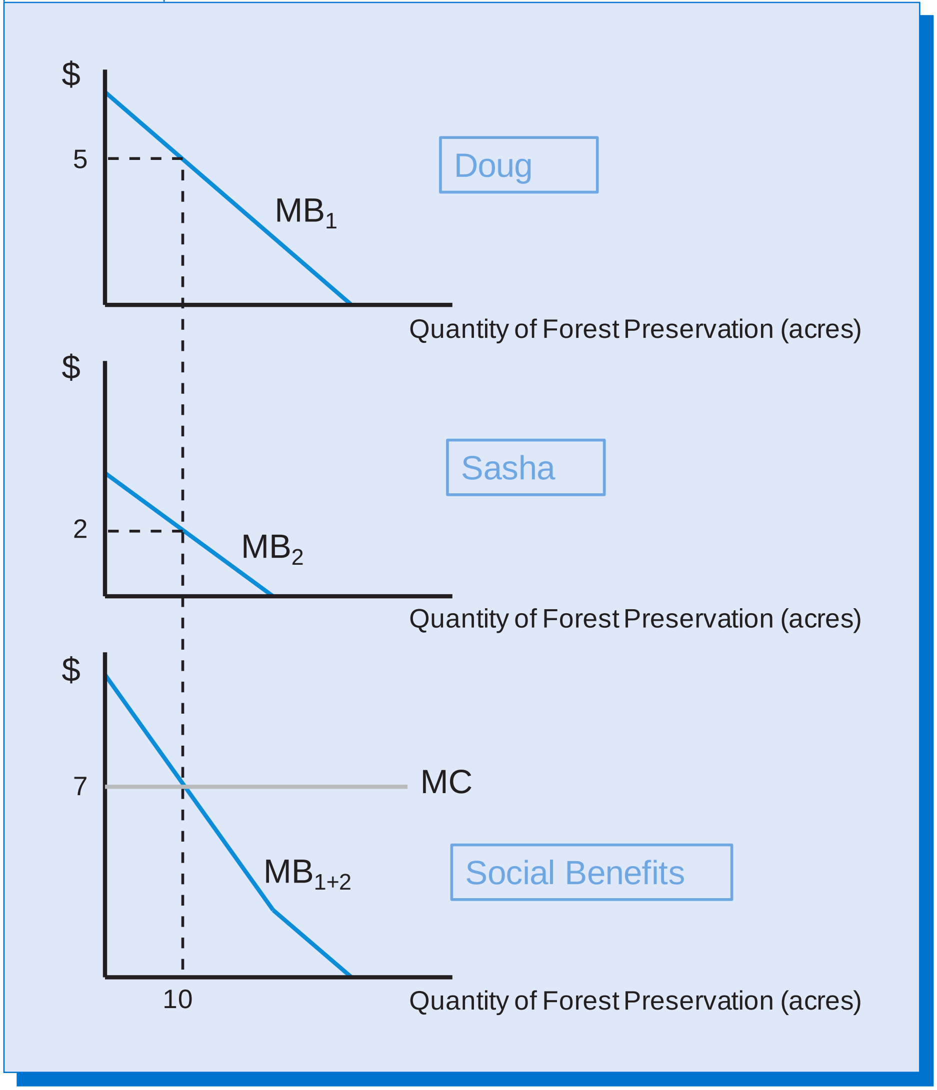
Suppose for simplicity that forest preservation costs society a constant $7 per acre, in terms of administrative and management costs. This is shown in the bottom graph in Figure 4.4. In this example, the optimal level of forest preservation is 10 acres—the point where the marginal **social benefits** just equal the marginal costs. But we have not addressed the question of how much Doug and Sasha are actually willing to pay for forest preservation. In the case of a public good, one's marginal benefit curve is not the same as his or her willingness-to-pay curve. For example, while Doug receives a marginal benefit of $5 for an acre of forest preservation, he has an incentive to be a free rider and he may be willing to pay only $3 per acre or nothing at all.

The problem is that we do not have a market in which people accurately indicate their preferences for public goods. Perhaps we could use a survey to collect information on how much people value certain public goods (we discuss economic surveys in Chapter 6), but even then people might not provide accurate responses. Ultimately, decisions regarding public goods require some kind of social deliberation. One possibility is to rely on elected officials to make public goods decisions for their constituents. Another is to rely on a democratic process, such as direct voting or local town meetings.

Even if we reach the "correct" level of provision from a social perspective, another problem arises due to differences across individuals. Suppose that we correctly determine that the appropriate level of forest preservation in Figure 4.4 is 10 acres. At a cost of $7 per acre, we need to raise $70 in revenues to pay for preservation. We might tax Doug and Sasha $35 each to cover these costs. Doug receives at least $5 in benefits for every acre preserved, or a total of at least $50 in benefits, so he might not object to the $35 tax. However, Sasha receives significantly lower benefits and she may view the tax as excessive.

Suppose that we extend our two-person example to the entire population of the United States—about 125 million households. If preferences in the general population are similar to Doug and Sasha's, we will need to raise about 125 million × $35, or over $4 billion for forest preservation in order to reflect the true social benefits in the country. This could be done with a tax of $35 per household. But, of course, marginal benefits vary across households. It is clearly impractical to assess the actual marginal benefit of each household and adjust the tax per household accordingly. A society-wide decision must be made. Some people might think that they have to pay too much; others, that the allocation of money for forest preservation is inadequate. But assessing a tax on everyone is essential to achieve the goal. The tax might be a constant $35 per household, or it might vary according to income or some other criteria. Debates regarding efficiency and fairness in the case of public goods are, thus, inevitably both political and economic in nature.

Figure 4.4 The Economics of Forest Preservation



4.3 THE GLOBAL COMMONS

In examining common property resources and public goods in this chapter, we have extended the scope of our resource and environmental analysis. A little thought should make it clear that these cases are closely related to the theory of externalities discussed in Chapter 3. In a sense, we are dealing here with special cases of externalities. The fisher who adds an extra boat to the fishing grounds imposes an external cost on all the other fishers by slightly lowering the average catch. An environmental organization that purchases and conserves important habitats confers an external benefit on all the rest of us, who may not have contributed to the effort but who gain a slightly improved environment.

The extension of the analysis to these examples, however, seems to raise another question. Can we really continue to define all these environmental issues as "externalities"? The use of the term seems to imply a secondary role in economic theory—external costs are added to economic analysis after the rest of the theory is essentially complete. But are these numerous externalities really symptoms of something more fundamental?

As we consider the multitude of environmental problems that have gained increased attention in recent years, we see the rising importance of cases involving common property resources and public goods. Global warming, ozone layer depletion, ocean pollution, freshwater pollution, groundwater overdraft, and species loss all have clear similarities to the cases discussed in this chapter. The increasing prevalence of such examples has led to a new focus on the concept of the **global commons**. If so many of the earth's resources and environmental systems show the characteristics of common property resources or public goods, perhaps we need to revise our way of thinking about the global economy.[11]

global commons global common property resources such as the atmosphere and the oceans.

Rather than focusing on the goals of economic growth and dealing with externalities as an afterthought, we need to recognize that the global economic system is highly dependent on the health of global ecosystems. Evaluation of the state of these systems and an assessment of how economic development can best be adapted to planetary limits is essential. This implies the need for new approaches to economic policy and new or reformed institutions at the national and international level. Clearly, this raises issues that go beyond the management of individual fisheries or national parks.

Proper management of the global commons poses special challenges because of the need to secure agreement among many different governments. Despite the many possibilities for conflicting views and free-rider temptations, several important international agreements, such as the Montreal Protocol on depletion of the ozone layer, have been put into place to deal with threats to the global atmosphere, oceans, and ecosystems. In other cases, such as the international negotiations on global climate change, effective agreements have been harder to achieve, as many countries wait for others to act or disagree about who should bear the costs.

We examine some of the implications of this broader perspective on common property issues in Chapter 9 and consider some issues of managing the global commons in later chapters, in particular in relation to the issue of global climate change in Chapters 12 and 13.

Summary

Common property resources are those that are nonexcludable and rival. Various systems are possible for managing such resources, including traditional understandings and government management. When no rules limit use, the resource is open access, meaning that anyone can use it without restriction. This situation leads to overuse of the resource and sometimes to the collapse of its ecological functions.

A classic case of the tragedy of the commons is overfishing of the oceans. Since there are no restrictions on access to fisheries in the open ocean, economic incentives lead to an excessive number of boats in operation. Depletion of the fish stocks results, with declining revenues for all fishers. But until economic profits (revenues minus costs) reach zero, there will continue to be an incentive for new participants to enter the fishery. This open-access equilibrium is both economically inefficient and ecologically damaging.

Possible policies to respond to overuse of the open-access resource include the use of licenses or quotas. Quotas can be assigned to individual fishing boats and can be made transferable (saleable). While there may be situations where local-level collective action can be effective in managing common property resources, as demonstrated by the research of Elinor Ostrom, with larger-scale resources government management of open-access resources is essential.

Similarly, active government policy is needed in the area of public goods provision. Public goods, once provided, benefit the general public rather than selected individuals. They include goods and services such as parks, highways, public health facilities, and national defense. No individual or group of individuals is likely to have sufficient incentive or funds to provide public goods, yet their benefits are great and often essential to social well-being. Many environmental public goods, such as forest and wetlands preservation, cannot be adequately supplied through private markets. Government intervention and public funds are needed to achieve the social benefits that flow from providing these public goods.

The global scope of many common property resources and public goods, including the atmosphere and oceans, raises many issues regarding proper management of the global commons. New and reformed institutions are needed to manage common property resources at the global level. The difficulty often lies in establishing effective international authority to regulate activities that threaten global ecosystems.

Key Terms and Concepts

absolutely diminishing returns
average cost
average revenue
common property resource
constant returns to scale
diminishing returns
economic profit
free riders
global commons
individual transferable quotas
license fee
marginal benefit
marginal costs
marginal revenue
nonexclusive good
nonrival good
open-access equilibrium
open-access resources
overfishing
profits
public goods
quota
rival good
social benefits
total cost
total product
total revenue
tragedy of the commons
vertical addition

Discussion Questions

1. Would a good policy for fishery management aim to obtain the maximum sustainable yield? Why or why not? When we speak of an optimal equilibrium from an economic point of view, will this equilibrium also be generally ecologically sound? What might cause economic and ecological principles to conflict with fisheries management?

2. Suppose that the fishery example discussed in the chapter was *not* a common property resource but a fishery in a lake owned by an individual or a single firm. The owner could choose to allow fishing and charge a fee for access to the lake. How would the economic logic differ from the common property resource case? Would there be a greater net social benefit? Who would receive this net social benefit?

3. Discuss the effects of technological improvement in an industry that uses a common-property resource. For example, consider a technological improvement in fishing equipment that makes it possible to cut the costs of a fishing boat trip in half. Technological progress usually increases net social benefit. Does it do so in this case? How would your answer be affected by government policies relating to this industry?

4. Do you think it is possible to draw a clear distinction between private and public goods? Which of the following might be considered public goods: farmland, forest land, beachfront property, highways, a city park, a parking lot, a sports arena? What rules of the market or of public policy should apply to the provision of these goods?

Exercises

1. Farmers in an arid region of Mexico draw their irrigation water from an underground aquifer. The aquifer has a natural maximum recharge rate of 340,000 gallons per day (i.e., 340,000 gallons per day filter into the underground reservoir from natural sources). The total product schedule for well operations looks like this:

Wells Operating	10	20	30	40	50	60	70	80	90
Total Water Output (Thousand Gal./Day)	100	200	280	340	380	400	400	380	340

The cost of operating a well is 600 pesos per day; the value of water to the farmer is 0.1 pesos per gallon.

a) Adding a new row to the table above, calculate total revenue for each number of wells.
b) If each well is privately owned by a different farmer without any regulations, how many wells will operate? (To calculate this, you will need to calculate average revenue for each number of wells. Solve to the nearest multiple of 10 wells.) Briefly describe why this number of wells is not economically efficiency. Also, is this number of wells likely to be ecologically sustainable in the long-term? Why or why not?
c) What would be the economically efficient number of wells? (To calculate this, you will need to calculate marginal revenue, best shown *between* two levels of output. Again, just solve to the nearest multiple of 10 wells.) Explain why social benefits (profits) are maximized at this level of output.
d) Describe one policy that could be implemented to achieve the socially efficient equilibrium. Also, is the socially efficient equilibrium likely to be ecologically sustainable?
e) Suppose a new technology is adopted that reduces the cost of operating a well from 600 to 400 pesos. Now how many wells (to the nearest multiple of 10) will operate without any regulation?
f) What is the socially efficient (i.e., profit maximizing) number of wells with the new technology? How has the introduction of this new technology affected environmental sustainability? Would you recommend any additional regulation after the introduction of the new technology?

2. Four towns share a common water source. By buying open land along the watershed (area from which the water flows) they can preserve its purity from sewage, road runoff, etc. The land demand schedule for each town based on water treatment costs saved can be expressed as:

$$P = \$34{,}000 - 10\ Q_d$$

where Q_d is acres purchased, and P is the price per acre that the town would be willing to pay.

a) If the cost of land is $30,000 per acre, how much land will be purchased if each town operates independently?
b) Suppose the four towns form a joint commission for land purchases. Now how much land will be purchased? Show the situation graphically. (If the economic theory is not clear, imagine representatives of the four towns sitting around a table, discussing the costs and benefits of purchasing different amounts of land.)
c) What is the socially efficient solution and why? Discuss this in terms of the demand for clean water. Is clean water a public good in this case? Can water generally be considered to be a public good?
d) Suppose that the price of land was $36,000 per acre instead. Now how many total acres would be purchased if each town acted independently? How many acres would be purchased if they formed a joint commission?

Notes

1. Note that in this example we use a long-term production function that represents the fishery product over time. Decline, or collapse, of fisheries, as shown in the absolutely diminishing returns section of the graph, would not take place in a single period but over several years.
2. You might wonder why more boats continue to operate even though the profit per boat, while still positive, becomes rather small. Our explanation assumes, for example, that even if the profit per boat is very small, say only $50, more fishers will still be attracted to enter the industry. We are assuming that the profits in this example represent *economic profits*, which are the profits measured relative to the fishers' next-best alternative. So as long as such profits are positive, fishing is more attractive than the next-best alternative, and there is further incentive to send more boats.
3. This concept was first introduced in Hardin, 1968. A more recent assessment of the issue is given in Feeny *et al*., 1999.
4. Note that a true marginal analysis would require data on how total revenues change with each additional boat, rather than each additional 100 boats. Thus our analysis involves some approximation between the values given in the tables.
5. A normal profit is the minimal profit a business needs to make to remain in the industry. It is equal to the profit that could be made in the next-best alternative.
6. For an extensive treatment of the economic analysis of fisheries and other natural resources, see Clark, 1990.
7. See Ostrom, 1990.
8. The formal definition of a public good is a commodity or service that, if supplied to one person, can be made available to others at no extra cost (Pearce, 1992). A "pure" public good is one which the producer is unable to exclude anyone from consuming. Thus a pure public good demonstrates both nonrival consumption and nonexcludability.
9. Technically, National Parks are not a "pure" public good since it is possible to charge an entry fee, thereby excluding those who do not pay the fee. But the National Parks remain a public good so long as it is national policy to allow free or low-fee entry.

10. The National Park system does receive some funding from voluntary donations to the National Park Foundation, a nonprofit organization set up by Congress to support the National Parks.
11. See Heal, 1999, and Johnson and Duchin, 2000, on the concept of the global commons.

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Web Sites

1. **www.iasc-commons.org.** Links to articles related to management of common pool resources. The site is managed by the International Association for the Study of Common Property, "a nonprofit Association devoted to understanding and improving institutions for the management of environmental resources that are (or could be) held or used collectively by communities in developing or developed countries."
2. **www.garretthardinsociety.org/info/links.html.** Numerous web links to writings and organizations related to commons issues, published by the Garrett Hardin Society, including Hardin's original 1968 article on the tragedy of the commons.

CHAPTER 5

Resource Allocation Over Time

Chapter 5 Focus Questions

- How should we decide to allocate nonrenewable resources across different generations?
- How can we value resource consumption that will take place in the future?
- What will happen to prices and consumption if resources start to run out?

5.1 ALLOCATION OF NONRENEWABLE RESOURCES

renewable resources resources that are regenerated over time through ecological processes, such as forests and fisheries, but can be depleted through exploitation.

nonrenewable resources resources that do not regenerate through ecological processes, at least on a human time scale, such as oil, coal, and mineral ores.

Resources can be **renewable** or **nonrenewable**. Renewable resources, if properly managed, can last indefinitely. Think of a well-managed farm, forest, or fishery—we expect that such resources can continue to be productive for centuries. Nonrenewable resources, by contrast, cannot last forever. Examples include deposits of copper ore and crude oil supplies. This raises the issue of how much of these limited nonrenewable resources we use today and how much we save for future generations. A common concern is that we are using up Earth's nonrenewable resources too rapidly. But others contend that technological progress and adaptation will avoid resource shortages. What does economic theory have to say about this issue?

A simple version of nonrenewable resource analysis begins by assuming that we have a known, limited quantity of a resource that we can use during two different periods. The supply of high-grade copper, for example, is relatively fixed in amount.[1] How should we allocate this limited resource between current and future periods?

A simple initial model of nonrenewable resource allocation deals only with two time periods. (If we consider all possible future periods, the problem becomes more complex, though not theoretically insoluble, as we will see). Our economic analysis weighs the economic value of copper to society in the present as compared with the value of copper in the future. Owners of copper deposits will decide whether to exploit them immediately or to hold them for a future period based on an estimate of probable future prices. We can initially formulate the problem as a simple extension of standard supply and demand theory.[2]

Equilibrium in the Current Period

First, let us consider only the present period. Figure 5.1 shows a hypothetical supply and demand curve for copper. From this, we can derive the **marginal net benefit** curve for copper, which shows the difference between the value to the consumer and the cost of supply for each unit of copper. For example, if we can extract a ton of copper for a cost of $50 and its value to the purchaser (i.e., maximum willingness to pay) is $150 per ton, its marginal net benefit is $100. Note that the marginal net benefit to society is simply the sum of the consumer surplus and the producer surplus for each unit sold.

marginal net benefit the net benefit of the consumption or production of an additional unit of a resource. Marginal net benefits are equal to marginal benefits minus marginal costs.

Graphically, marginal net benefit is the vertical difference between price on the supply curve and price on the demand curve. Marginal net benefits are generally largest for the first units extracted, then decline to zero at equilibrium (where the supply and demand curves meet). If we were to produce more than the equilibrium quantity, marginal net benefits would become negative as supply costs rise above the value to the purchaser.

The marginal net benefit concept is a handy way of compressing into one curve information about both supply and demand in one period. The marginal net benefits of copper, based on the supply and demand curves in Figure 5.1, are shown by curve MNB in Figure 5.2.

Figure 5.1 Supply and Demand for Copper

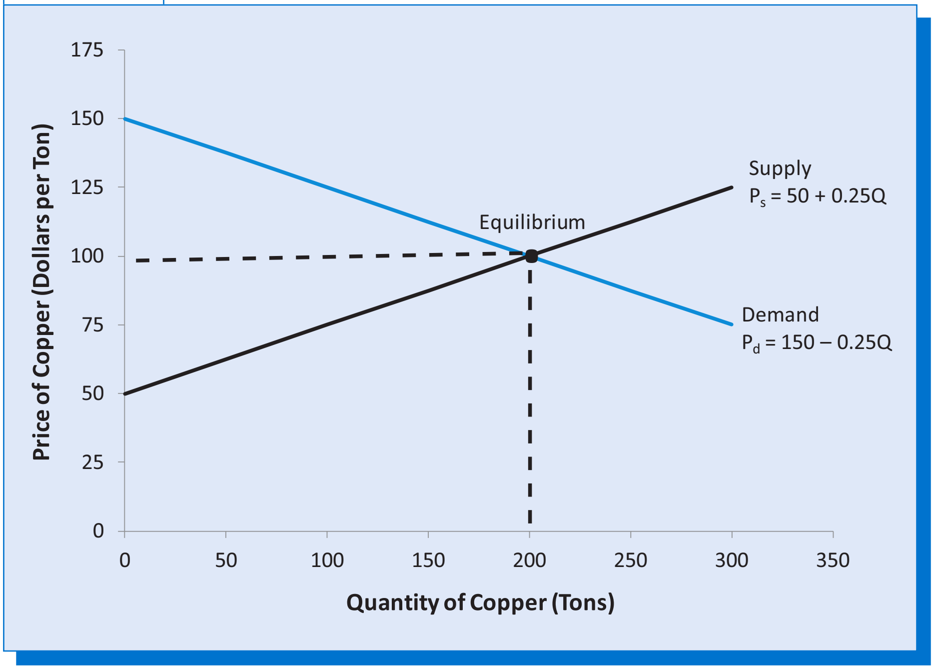
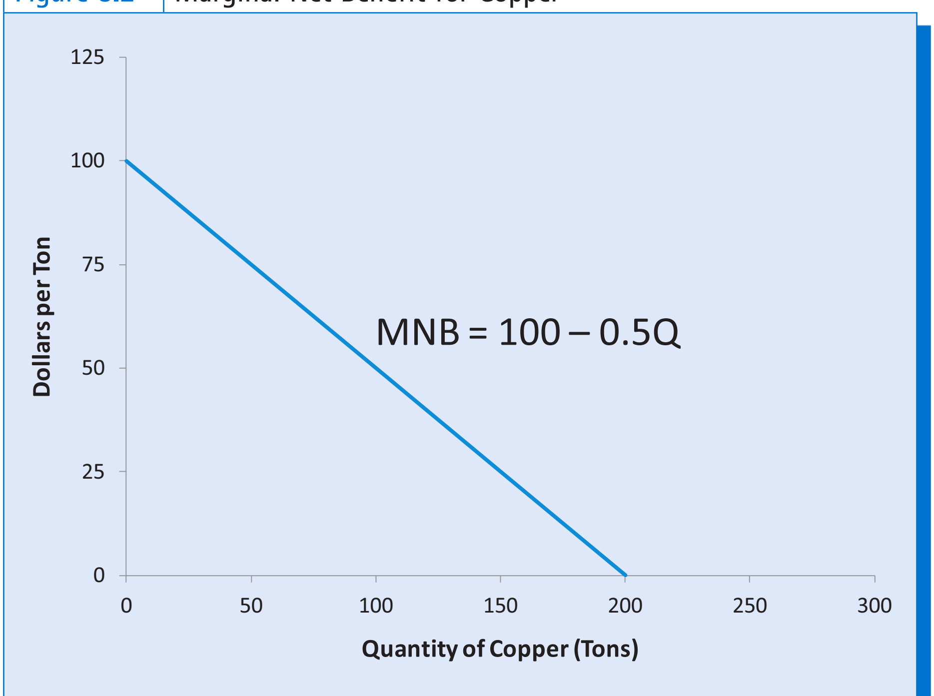


Figure 5.2 Marginal Net Benefit for Copper



Algebraically, if the demand and supply schedules are given by

$$P_d = 150 - 0.25Q$$

and

$$P_s = 50 + 0.25Q$$

then marginal net benefit is given by

$$MNB = P_d - P_s = [(150 - 0.25Q) - (50 + 0.25Q)] = 100 - 0.5Q.$$

total net benefit total benefit minus total cost.

At the supply and demand equilibrium of Q = 200, marginal net benefit is 0, indicating that producing and consuming more than 200 tons of copper will provide no additional net benefit. The area under the marginal net benefit curve shows **total net benefit** (just as the area under a demand curve shows total benefit and the area under a supply curve shows total cost). In this case, total benefits are equal to the area under a triangle with a height of \$100 per ton and a length of 200 tons. Using the formula for the area of a triangle, (base*height*0.5), we get total net benefits of \$10,000.

static equilibrium a market equilibrium that results when only present costs and benefits are considered.

When marginal net benefits are just equal to zero, total net benefits are maximized. This corresponds to the market equilibrium, at a quantity of 200 and a price of \$100 per ton. We will call this the **static equilibrium**—the market equilibrium that will prevail if only present costs and benefits are considered.[3]

Now let's consider the marginal net benefit of copper in the second period. We cannot know this value for sure, of course, because no one can foretell the future, but we *do* know in our simple model that a fixed quantity of copper must be divided between the two periods. Let's make a simplifying assumption that the marginal net benefits of the copper market in Period 2 will be *exactly the same* as in Period 1. In other words, the supply and demand curves will be unchanged in the second time period. (This assumption is not necessary for the analysis, but it will make our example simpler.)

A graphical trick allows us to compare net benefits across the two periods. We use the horizontal axis to measure the total available quantity of copper—say, 250 tons—and put the marginal net benefit curve for the first period, MNB_1, on this graph in the same way we did in Figure 5.2. Then we put the marginal net benefit curve for the second period, MNB_2, on the graph in mirror-image fashion, going from right to left. Thus we have two horizontal scales, with the quantity used in Period 1 (Q_1) shown left-to-right, and the quantity used in Period 2 (Q_2) shown right-to-left (Figure 5.3). At any point on the horizontal axis, the total quantity used in the two time periods adds up to 250 tons, the total available.

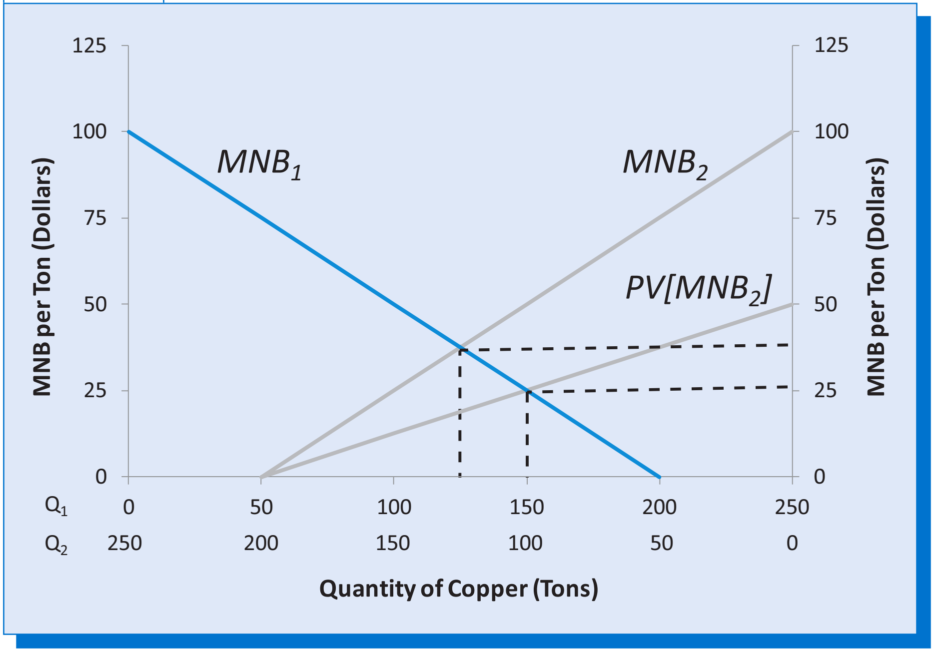
present value the current value of a stream of future costs or benefits; a discount rate is used to convert future costs or benefits to present values.

discount rate the annual rate at which future benefits or costs are discounted relative to current benefits or costs.

One more step will complete our analysis. Because we want to compare two time periods, we must translate future values into their equivalent in present values. The economic concept of **present value** relies on the use of a **discount rate** to convert future to present monetary values. Suppose, for example, I promise to give you \$1,000—ten years from now. What is the value of this promise today?

Assuming I am trustworthy, and you will definitely receive the money, the answer depends on the discount rate, reflected in financial

Figure 5.3 Allocation of Copper over Two Time Periods



terms as a rate of interest on deposits. Suppose there is a 7.25 percent interest rate.[4] Five hundred dollars put in the bank today at compound interest would be worth approximately $1,000 in ten years. We can say that the present value of the $1,000 to be received ten years from now is equal to $500 in cash today. In other words, you would be equally well off with $500 today or $1,000 ten years from now.[5]

Applying this principle to our copper example, let's assume that the two periods in our copper extraction example are ten years apart. (This assumption of only two extraction periods separated by ten years is, of course, unrealistic—but the principle that emerges from this mathematically simple example can be generalized to an *n*-period model.) Using the present value method, we can convert the marginal net benefits of copper in Period 2 into equivalent Period 1 values. We do this using the formula:

$$PV[MNB_2] = MNB_2 \,/\, (1+r)^n,$$

where r is the annual discount rate and n is the number of years between periods.

If $r = 0.0725$ or 7.25 percent, and $n = 10$, then we can closely approximate $PV[MNB_2]$ as

$$PV[MNB_2] = MNB_2 \,/\, (1.0725)^{10} \approx MNB_2 \,/\, 2.$$

This present value of the marginal net benefits in Period 2 is shown in Figure 5.3 as a line with a slope half as great as the undiscounted MNB_2. In other words, the marginal net benefits in the second period are reduced by a factor of two.

Dynamic Equilibrium for Two Periods

The reason for the special graphical format now becomes apparent. Consider the point where the two curves MNB_1 and $PV[MNB_2]$ cross. At this point the present value of the marginal net benefit of 1 ton of copper is *the same* in both time periods. This is the optimal economic allocation between periods, since at this point no additional net benefit can be obtained by shifting consumption from one period to another. As you can see from the graph, this optimal allocation is 150 tons in Period 1 and 100 tons in Period 2. Algebraically this solution is obtained by solving a system of two equations:

$$MNB_1 = PV[MNB_2]$$

and

$$Q_1 + Q_2 = 250.$$

supply constraint an upper limit on supply, for example, of a nonrenewable resource.

The second equation is the **supply constraint**, which tells us that the quantities used in the two periods must sum to exactly 250 tons, the total quantity available.

We can solve the system of equations by first setting the two marginal net benefit curves equal to each other:

$$MNB_1 = PV[MNB_2], \text{ or } (100 - 0.5Q_1) = (100 - 0.5Q_2) \ / \ 2$$
$$100 - 0.5Q_1 = 50 - 0.25Q_2$$

Because $Q_1 + Q_2 = 250$, $Q_2 = 250 - Q_1$. Substituting this in, and solving for Q_1, we have:

$$100 - 0.5Q_1 = 50 - 0.25(250 - Q_1)$$
$$100 - 0.5Q_1 = 50 - 62.5 + 0.25Q_1$$
$$0.75\ Q_1 = 112.5$$
$$Q_1 = 150 \text{ tons}$$

Once we've solved for Q_1, we can easily solve for Q_2 given that $Q_1 + Q_2$ must equal the supply constraint of 250 tons. Thus Q_2 is 100 tons.

We can check the assertion that this solution is economically optimal by using welfare analysis (see Figure 5.4). By choosing the equilibrium point where $Q_1 = 150$ and $Q_2 = 100$, we have achieved maximum total net benefit, shown by the shaded area A + B in Figure 5.4. (Area A, the blue-shaded region, is the total net benefit in the first period; area B, the gray-shaded region, is the total net benefit in the second period.)

Compare this result with the welfare effects of any other allocation, for example the allocation $Q_1 = 200$, $Q_2 = 50$. As shown in Figure 5.5, total welfare for the two periods is less with this new allocation (by the area B_2). By shifting 50 tons from Period 2 use to Period 1 use, we have gained a Period 1 benefit equal to A_2. (Note that area A_1 in Figure 5.5 is equal to area A in Figure 5.4). But we have lost a Period 2 benefit equal to $A_2 + B_2$, for a net loss of B_2. Total welfare is now $A_1 + A_2 + B_1$, less than the area A + B in Figure 5.4. Similarly, any other allocation we can try will prove inferior to the optimal solution of $Q_1 = 150$, $Q_2 = 100$. (Try, for example, $Q_1 = 100$, $Q_2 = 150$. Show the effect of this allocation on total net benefits.)

User Costs and Resource Depletion Taxes

Let's translate what we have learned from this algebraic and graphical analysis into more commonsense terms. We know that we can increase our benefits today by using more copper (in this example up to 200 tons, which is the most we would use today if we took no account of future needs). If we chose to use only 50 tons today, 200 tons would be left for the next

Figure 5.4 Optimal Intertemporal Resource Allocation

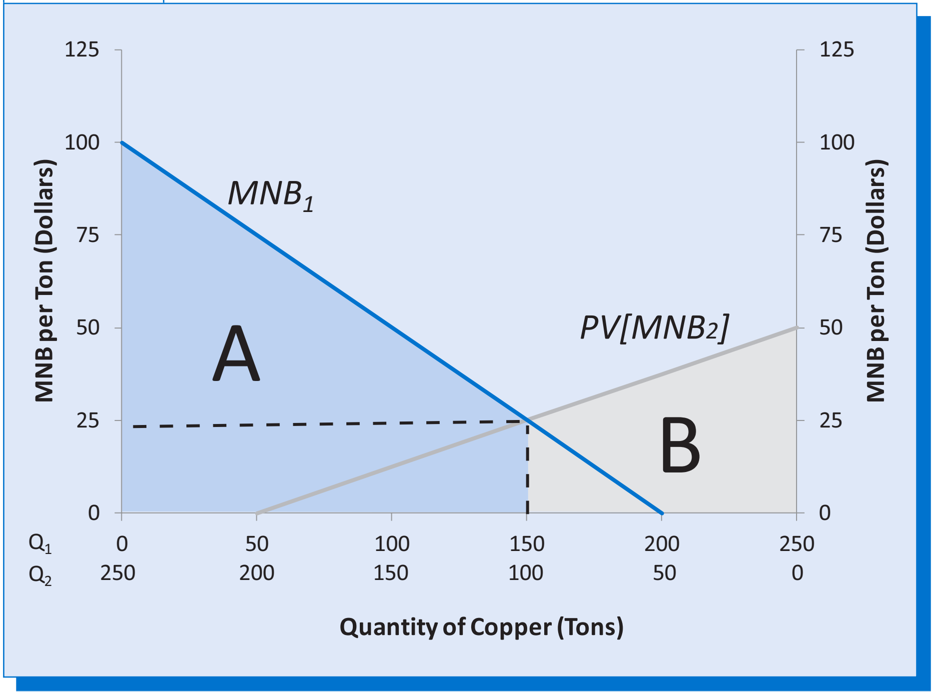
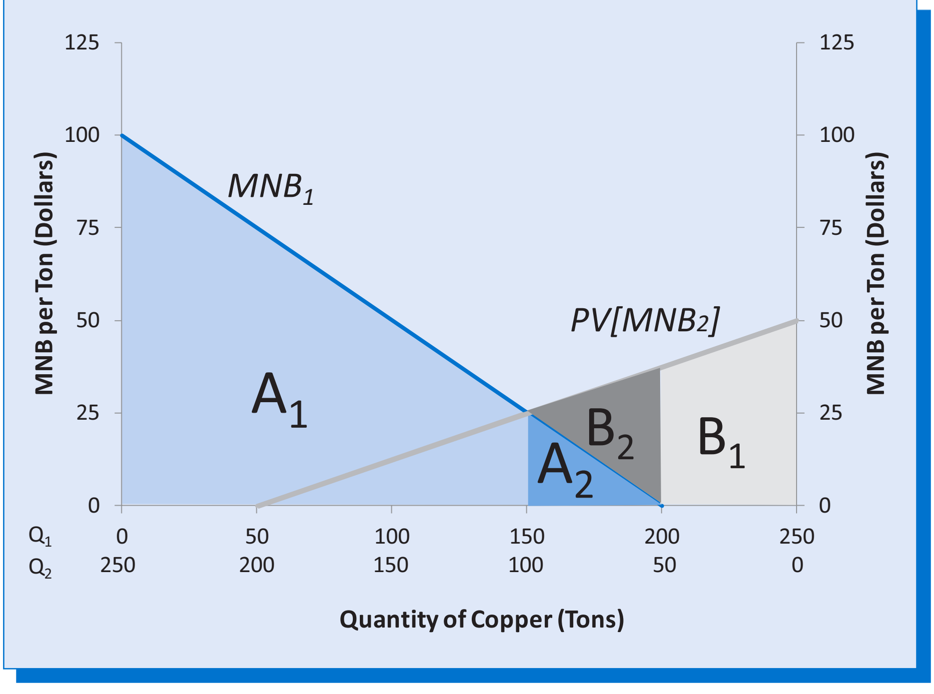


Figure 5.5 Suboptimal Intertemporal Resource Allocation



period—enough to fulfill the maximum demand in that period. But at any use level greater than 50 tons, we start to cut into the amount of copper that the second generation would like to use.

user costs opportunity costs associated with the loss of future potential uses of a resource, resulting from consumption of the resource in the present.

Another way of putting this is to say that we start *imposing costs on future consumers of copper* by using up more than 50 tons of copper today. On our graph in Figure 5.4, those **user costs** show up as the steadily rising curve $PV[MNB_2]$—the lost benefits in the future from using additional copper in the present. The more we use today, the less is available for the future, and the higher these costs become. User costs are really just a different kind of third-party cost or externality—an externality in time.

We can justify using up copper today so long as the marginal benefits from doing so outweigh the user costs imposed on future citizens. But when the user costs become higher than the marginal benefits from consumption today—in our example, at any level of present consumption above 150 tons—we are reducing total economic welfare (i.e., the sum of welfare in both time periods) by our excessive present consumption.

Going back to our algebraic and graphical analysis, we define an exact value for the user cost at the Period 1 consumption level that we have determined to be optimal. The vertical distance at the intersection point of MNB_1 and $PV[MNB_2]$ in Figure 5.4 shows the user cost at equilibrium. We can calculate this easily by evaluating either MNB_1 or $PV[MNB_2]$ at the intersection point where $Q_1 = 150$ and $Q_2 = 100$:

$$User\ Cost = MNB_1 = 100 - 0.5(150) = 25$$

or

$$User\ Cost = PV[MNB_2] = 50 - 0.25(100) = 25.$$

The user cost at equilibrium is thus \$25. Note that we should get the same answer using either MNB curve.

So how can we obtain the optimal allocation across time? If we have an unregulated market in the first time period, normal market forces will result in production and consumption of 200 tons—too much from the perspective of an efficient intertemporal allocation. We should only produce and consume 150 tons in the first time period.

Suppose we go back to the original supply and demand schedules for Period 1 (redrawn in Figure 5.6). If we do not consider Period 2 at all, the market equilibrium in Period 1 will be 200 tons of copper at a price of \$100. Now suppose we add to the ordinary supply costs the user costs derived from Figure 5.4—just as we added an environmental externality cost to the ordinary supply costs in Chapter 3. Remember that the user costs are the marginal lost benefits in Period 2, a kind of "externality in time." The result is shown in Figure 5.6 as the **social cost** schedule S'.

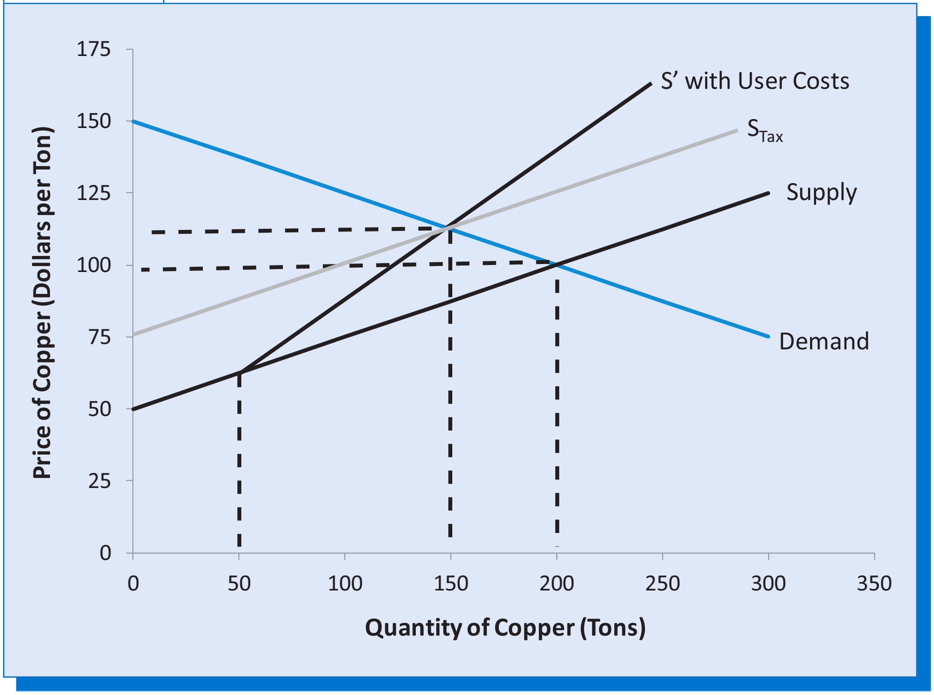
social cost the market and nonmarket costs associated with a good or service.

A new equilibrium appears at 150 units of copper consumption, with a price of \$112.50 per ton (as we'll see below). The user cost at this new equilibrium is \$25—the vertical distance between the original supply curve and the new social cost curve S'.

resource depletion tax a tax imposed on the extraction or sale of a natural resource.

What policy can we use to get us to the efficient outcome (quantity of 150 tons and a price of \$112.50 per ton) in Period 1? Recall that we internalized a negative externality in Chapter 3 by using a Pigovian tax. In this case, we can internalize the externality of user costs by implementing a **resource depletion tax**. The "correct"

Figure 5.6 Market for Copper with User Costs (First Period)



resource depletion tax in Period 1 is the amount that fully internalizes the user costs at the optimal quantity in Period 1. So the correct resource depletion tax is \$25 per ton, as shown in Figure 5.6. In other words, a resource depletion tax of \$25 per ton reduces the Period 1 equilibrium to the efficient quantity of 150 tons.

Once we have solved for the user costs at the optimal allocation as we have done above, equal to \$25 per ton, we can solve for prices in the first and second time periods. For Period 1 we use the original equations for the supply and demand curves, but add the \$25 resource depletion tax to the supply curve to internalize the user cost. For the first period, this gives us:

$$P_d = 150 - 0.25Q_1 \text{ and } P_s = 75 + 0.25Q_1.$$

Setting these equal and solving we get the first period equilibrium:

$$Q_1 = 150, P_1 = 112.5.$$

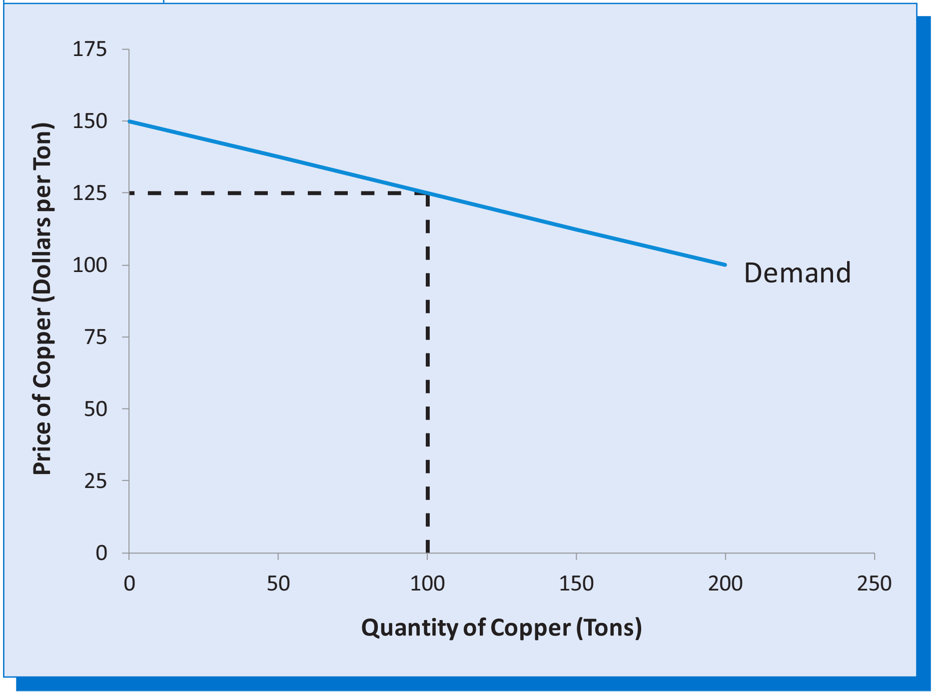
With a first-period consumption of 150 tons, 100 tons will remain for consumption in the second period, at a second-period price of \$125 per ton (assuming demand conditions are unchanged). This is shown in Figure 5.7. Using the demand curve equation, the equilibrium price can be calculated mathematically by substituting in the known quantity of 100 tons to get:

$$P_2 = 150 - 0.25(100) = 150 - 25 = \$125/\text{ton}.$$

If user costs are internalized in this fashion, the new market equilibrium, known as a **dynamic equilibrium**, reflects *both* the needs

dynamic equilibrium a market equilibrium that results when present and future costs and benefits are considered.

Figure 5.7 Market for Copper (Second Period)



of the present and of the future. The higher price in the current generation will send a signal to producers and consumers of the resource to produce and use less today, thereby conserving more for the future.

A resource depletion tax is not the only policy approach for the efficient allocation of a resource across time. Other policy mechanisms could include direct government control of resource exploitation, setting aside resource deposits or maintaining stockpiles. But in certain cases, the market may not need government intervention to internalize user costs. This would be true especially if the period until expected resource exhaustion is relatively short. In this case, private owners of the resource will anticipate the second-period situation and act accordingly.

If resource shortages are foreseen, profit-seeking resource owners will hold some copper stocks off the market or leave copper ores in the ground in order to wait for higher future profits. We can understand this logic by noting that if the market goes to equilibrium in the first time period, at 200 tons, the marginal profit on the last few units sold is rather small, only a few dollars (i.e., the vertical difference between the supply curve and price in Figure 5.1). If only 50 tons were then available in Period 2, copper producers could charge as much as consumers are willing to pay for this limited quantity. We can solve for this price by inserting a quantity of 50 tons into the demand curve, equal to $137.50 per ton. But the marginal costs of supplying 50 tons of copper are quite low. Thus the large vertical difference between the demand curve and the supply curve at a quantity of 50 tons represents large future profits.

> **scarcity rent** payments to resource owners in excess of the amount necessary to keep those resources in production.

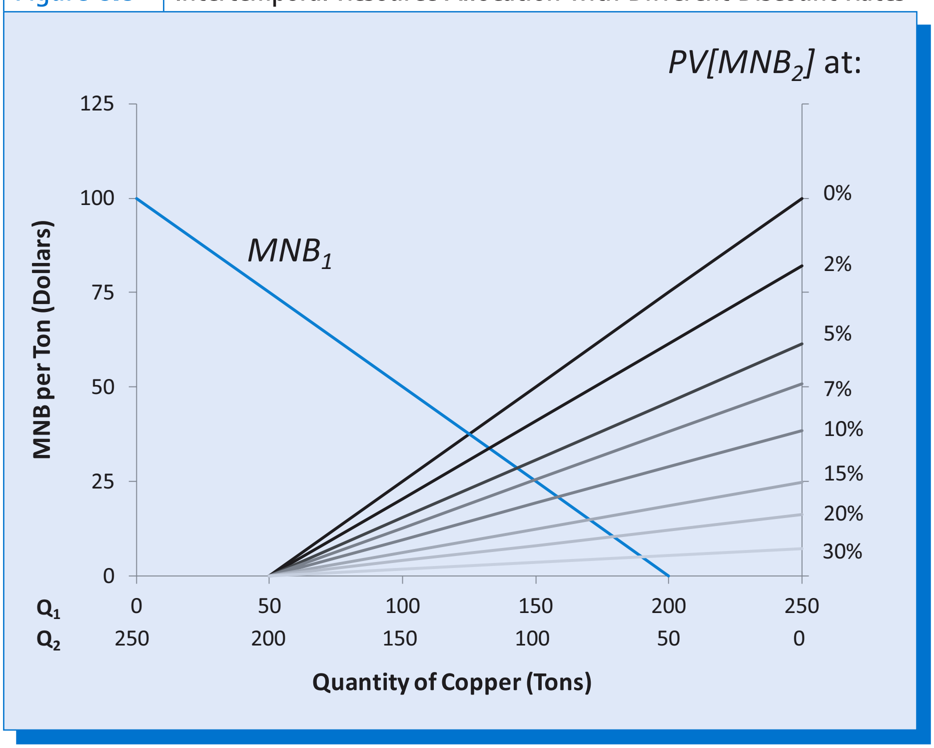
A payment to resource owners in excess of what is necessary to keep those resources in production is known as **scarcity rent**. Technically, the scarcity rent on a marginal unit of copper would be equal to the vertical distance between the price on the demand curve and the price on the supply curve, or the amount producers could charge above their production costs. In our example, copper owners have an incentive to reduce the quantity offered for sale in Period 1, foregoing some relatively small current profits, and instead obtain relatively large marginal profits in the future. Due to the limited quantity of copper available, copper producers will accrue scarcity rent.

We can demonstrate (though not shown here) that under certain assumptions the profit-maximizing behavior of copper producers will produce the *exact same allocation* of copper across the two time periods as the resource depletion tax. In other words, we would not need the resource depletion tax to achieve the efficient intertemporal allocation across the two time periods. But we may be justified in being skeptical as to how well markets alone can in fact foresee future resource limitations and produce efficient allocations. We address this issue in the next section.

5.2 HOTELLING'S RULE AND TIME DISCOUNTING

What if we want to consider the real world, which presents not two periods but an infinite number of future periods? How much copper should we be prepared to set aside for 50 years from now? One hundred years? Extending our two-period analysis to a more general theory offers perspective on these issues. Such questions test the limits of our economic model and also address the interrelationship between social values and the more specific market values that we normally deal with in economic theory.

Figure 5.8 Intertemporal Resource Allocation with Different Discount Rates



Our simple two-period example makes clear that the discount rate is a critical variable. At different discount rates, the optimal allocation of copper between the two periods will vary significantly. Let's start at one extreme—a discount rate of zero. In our example, the equilibrium allocation of copper would be 125 units consumed in each period. At a discount rate of zero, future net benefits are given *exactly the same value* as if they were current net benefits. The available copper is, therefore, divided evenly between the periods.

At any discount rate above zero, we favor present consumption over future consumption to some degree. At a very high discount rate—say 30 percent per year—the first period allocation of copper is 190 tons, close to the 200 tons consumed in the static equilibrium case, and user costs fall to only $5. High discount rates have the effect of weighing present benefits much more heavily than future benefits (see Figure 5.8 and Table 5.1).

Hotelling's rule a theory stating that in equilibrium the net price (price minus production costs, or the scarcity rent) of a resource must rise at a rate equal to the rate of interest.

We can extend this logic from one period to many periods, and even to an infinite future. The principle involved is known as **Hotelling's rule**. This rule states that in equilibrium the resource net price (defined as the price minus extraction costs, or scarcity rent) must rise at a rate equal to the rate of interest.[6]

Consider an example from the perspective of a copper ore deposit owner. The owner's profit per ton extracted is equal to the net price (i.e., the selling price minus their marginal costs). In deciding whether to produce and sell the copper, the owner will weigh the net price available today against a possible higher future net price, as we discussed previously. If the present net price plus interest exceeds the probable future net price, the owner will profit more by extracting the resource today and investing the proceeds, rather than waiting. If the expected future net price is higher than the net price today plus interest, it will be more profitable to wait and sell at the future date.

If all resource owners follow this logic, the quantity of copper supplied today will increase until today's net price of copper falls low enough to encourage resource owners to conserve, hoping for a better future price. At this point, Hotelling's rule will hold: The expectations of future net price increases will exactly follow an exponential curve $P_1(1+r)^n$, where P_1 is today's price, r is the discount rate, and n is the number of years from the present (see Figure 5.9).

If this sounds confusing, consider this simpler, commonsense formulation: High discount rates create an incentive to use resources quickly (since their present value is greater relative to their future value); low discount rates create greater incentive to conserve. More generally, we

Table 5.1 **Intertemporal Resource Allocation with Different Discount Rates**

Discount Rate (%)	$(1 + r)^{10}$	Q_1	Q_2
0	1	125	125
2	1.2	132	118
5	1.6	143	107
7.5	2	150	100
10	2.6	158	92
15	4	170	80
20	6.2	179	71
30	13.8	190	60

can say that economic theory implies the existence of an **optimal depletion rate**. Under market conditions, a nonrenewable resource will be used up at a certain "optimal" rate, and this rate will be faster at higher discount rates.[7]

optimal depletion rate the depletion rate for a natural resource that maximizes the net present value of the resource.

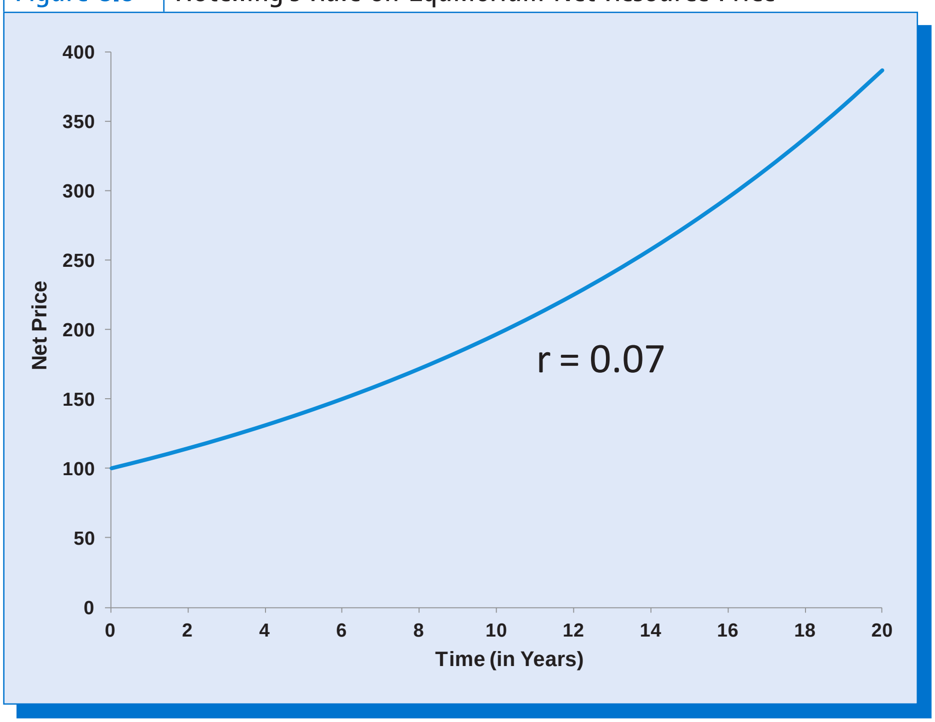
Interestingly, according to this theory it is optimal to deplete certain resources to complete exhaustion over time—the higher the discount rate, the shorter the time. Like the theory of optimal pollution, this sounds wrong to many people. What about the ethical imperative to leave something for future generations?

One way of answering this question is to say that we do not have an ethical imperative to leave untouched resources for future generations. Rather, we can leave them an economic system including an accumulation of capital that has been developed using these resources. If we use the resources today and squander the proceeds on frivolous consumption, that would indeed be unfair to future generations. But if we invest the proceeds wisely, resource use today will benefit both us and our descendants. This principle, expressed in economic terms, is known as the **Hartwick rule** (not to be confused with the similarly named and closely related Hotelling's rule). The Hartwick rule states that we should invest the scarcity rents from nonrenewable resources—the proceeds of resource sale, net of extraction costs—rather than consuming them. Thus we replace diminished natural resources with an equal value of produced capital.[8]

Hartwick rule a principle of resource use stating that resource rents—the proceeds of resource sale, net of extraction costs—should be invested rather than consumed.

A broader critique of discounting focuses on the fact that a discount rate based on standard commercial rates of interest will typically give a low weight to the well-being of future generations, especially far into the future. This leads some people to question whether we can

Figure 5.9 Hotelling's Rule on Equilibrium Net Resource Price



justifiably apply present-value analysis, based on a discount rate, over long periods. This issue will be important in our discussion of cost-benefit analysis in Chapter 7.

Another issue that affects the theory of exhaustible resources concerns the presence of environmental externalities in resource extraction. In this chapter we simply assumed no externalities in the production of copper, so the supply and demand curves for copper accurately reflect its social costs and benefits. In the real world, copper mining is likely to have significant environmental impacts. As higher-quality copper ores are used up, the environmental costs of recovering copper from lower-grade ores will probably rise. Internalizing these costs would affect the market price and intertemporal allocation of copper. In addition, a market for recycled copper is likely to develop, providing a new source of market supply not considered in our basic analysis. Issues such as these are dealt with more fully in Chapter 17.

Summary

Nonrenewable resources can be used in the present or conserved for future use. Economic theory offers some guidance concerning the optimal way to allocate nonrenewable resources over time. In essence, the net value gained from using a resource today must be balanced against the net value of its potential future use. To compare values across time periods, we use a discount rate to measure the present value of future consumption.

The concept of user costs captures the idea that by using resources today, we impose some cost on future potential consumers. User cost is kind of an externality in time and, like other externalities, should be reflected in market prices to internalize all social costs. Including user costs in market prices will reduce consumption today, leaving more for future use.

If resource owners accurately foresee future resource shortages, current prices will reflect user costs. The expectation that prices will rise creates an incentive to hold resources off the market today, in order to sell them at a higher net price in the future. According to Hotelling's rule, in equilibrium the net price of a resource (market price minus extraction costs) must rise at a rate equal to the rate of interest. The higher the interest rate, the more likely the owner is to profit from extracting and selling a nonrenewable resource today rather than waiting for higher prices in the future.

When considering long periods, discounting reduces the significance of user costs almost to zero and creates little market incentive for conserving nonrenewable resources. If governments wish to ensure a long-term supply of certain resources, they can internalize user costs through a resource depletion tax—much as a pollution tax can be used to internalize current externalities.

The alternative may be to exploit nonrenewable resources to exhaustion, leaving no reserves for future use. A major question is whether it is appropriate to use current discount rates to determine the allocation of resources over the long term or whether there is a social obligation to conserve resources for future generations.

Key Terms and Concepts

discount rate
dynamic equilibrium
Hartwick rule
Hotelling's rule
marginal net benefit
nonrenewable resources
optimal depletion rate
present value

renewable resources

resource depletion tax

scarcity rent

social cost

static equilibrium

supply constraint

total net benefit

user costs

Discussion Questions

1. It has been argued that any government policy aimed at nonrenewable resource conservation is an unwarranted interference with the free market. According to this point of view, if a resource is likely to become scarce, the people most likely to realize this are the private investors and traders who deal in the resource. If they anticipate scarcity, they will hold stocks of the resource for future profit, driving up its price and leading to conservation. Any action by government bureaucrats is likely to be less well informed than those of profit-motivated private firms. Evaluate this argument. Do you think that there are cases in which government should step in to conserve specific resources? If so, which policy tools should they use?
2. How could the principle of allocation of resource over time be applied to environmental resources such as the atmosphere and the oceans? Would the same kind of conclusions about optimal depletion apply or not?

Exercise

Suppose we are analyzing the intertemporal allocation of oil. Assume a generation is 35 years, and we are concerned with only two generations. The demand and supply functions for oil in the present generation are given by:

$$\text{Demand: } Q_d = 200 - 5P \text{ or } P = 40 - 0.2Q_d$$
$$\text{Supply: } Q_s = 5P \text{ or } P = 0.2Q_s$$

where Q is expressed in millions of barrels and P is the price per barrel.

a) Draw a supply-and-demand graph showing the equilibrium price and quantity consumed in this generation in the absence of any consideration of the future. Solve for the equilibrium price and quantity algebraically.

b) Next, draw a graph showing the marginal net benefits from consumption in this period at all levels of consumption up to the equilibrium level. Express the marginal net benefit function (benefit minus cost) algebraically.

c) Suppose that the marginal net benefit function is expected to be the same for the next generation. But there is a discount rate (interest rate) of 4 percent per year, which for 35 years works out to be approximately equal to 4, or $(1.04)^{35}$. Total oil supply for both generations is limited to 100 million barrels. Calculate the efficient allocation of resources between the two generations and show this graphically, similar to Figure 5.4. (Hint: Set marginal net benefits equal for the two periods, remembering to include the discount rate.)

d) What is the appropriate resource depletion tax in the current generation? Include a curve showing the marginal user costs and the resource depletion tax in the market graph for the current generation. You can either draw a new graph or just add these two lines to your graph from part (a). Finally, calculate the new price, with the resource depletion tax, in the current generation.

e) Briefly describe how your answers would differ if we used a higher or lower discount rate (without solving numerically or drawing new graphs)?

Notes

1. According to the U.S. Geological Survey's 2015 Mineral Commodity Summary, known global copper reserves of 690 million metric tons are sufficient to meet current global demand for approximately 40 years.
2. This analysis assumes that there is no recycling of copper; the economics of recycling is considered in Chapters 14 and 17.
3. In this chapter we assume that copper production has no associated externalities. The impact of externalities on nonrenewable resource extraction is discussed in Chapter 17.
4. We assume here this is a real interest rate, corrected for expected inflation.
5. You might object that you would prefer to have an actual \$500 to spend today. But if this is your choice you can do it by borrowing \$500 at 7.25 percent interest. When the loan comes due in ten years, amounting to \$1,000 with interest, you can pay it off with my \$1,000 gift.
6. The rule is named for Harold Hotelling, who originated the modern theory of non-renewable resources in the 1930s (see Hotelling, 1931). There is a debate about how well Hotelling's rule works to describe the prices of real-world resources; we discuss this further in Chapter 17.
7. We examine the relationship of resource prices and resource extraction patterns in more detail in Chapter 17.
8. See Hartwick, 1977; Solow, 1986.

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CHAPTER

6 Valuing the Environment

Chapter 6 Focus Questions

- What are the different types of economic values?
- What techniques do economists use to estimate the value of the environment and natural resources in monetary terms?
- Does a monetary valuation of the environment provide a good basis for policy decisions?

6.1 TOTAL ECONOMIC VALUE

Almost everyone would agree that the environment has tremendous value to humanity, from the natural resources that provide the basic material inputs for our economy to the ecological services that provide us with clean air and water, arable soil, flood protection, and aesthetic enjoyment. Some of these values are expressed through market transactions. Using market data, economists can estimate the benefits consumers and producers obtain from marketed goods and services.

But many of the benefits we obtain from nature are not necessarily derived from market transactions. Coastal wetlands provide protection from storm surges during extreme weather events. Hikers obtain enjoyment and a sense of renewal from visiting a National Park. Others simply receive satisfaction from knowing that efforts are made to protect endangered species or conserve wilderness. Despite common perceptions, economists do recognize these values when analyzing the benefits of various policy options. It is incorrect to assume that an economist will necessarily recommend, say, cutting down trees to obtain financial benefits over keeping the forest intact for the purposes of wildlife habitat and recreation.

In traditional environmental economic analysis, however, the notion of "value" is generally not based on ethical or philosophical grounds. In standard economic theory, nature has value *only* because humans ascribe some value to it. Thus according to this viewpoint, species do not have an inherent right to exist. Instead, their "worth" derives from any values placed on their existence by humans. Similarly, no one has an inherent right to clean air. Instead, the benefits of clean air should be weighed against the value of the market goods that can be produced along with the pollution.

Some theorists—primarily ecological economists and some noneconomists—have challenged this view, suggesting instead a "rights-based" notion of value.[1] The idea that nonhuman species may have inherent rights goes beyond the human-centered or anthropocentric worldview usually adopted by traditional economists, as we discussed in Chapter 1. Ecological economists with an ecocentric worldview are more likely to suggest that the most fundamental source of value derives from ecosystem functioning and should not be limited by the human perceptions of value that form the basis for economic analysis. It may be impossible to reconcile theories of inherent rights and ecocentric perspectives with monetary valuation, but it is certainly possible to go beyond market value to take into account environmental and social factors, and economists have devoted considerable effort to doing so. For perhaps the most ambitious attempt to determine the value of "the environment" on a global scale, see Box 6.1.

How can we analyze tradeoffs between the benefits of marketed goods and services and the **nonmarket benefits** of ecological services and environmental amenities? Many economists believe that in order to make a valid comparison we first need to quantify all these benefits using a common metric. As you might guess, the standard metric normally used by economists is some monetary unit, such as dollars. Thus the central challenge for nonmarket valuation becomes expressing various benefits and costs in monetary terms.

> **nonmarket benefits** benefits not obtained from goods and services sold in markets.
>
> **willingness to pay (WTP)** the maximum amount of money people are willing to pay for a good or service that increases their well-being.

First, let's consider the benefits that we receive from natural resources and the environment. Recall from Chapter 3 that marketed goods and services provide benefits to consumers as defined by the difference between their maximum willingness to pay and price, that is, consumer surplus. The same notion can be applied to nonmarket goods and services. The economic value that people obtain from a specific resource is defined as their maximum **willingness to pay (WTP)** for it.

Box 6.1
VALUING THE GLOBAL ECOSYSTEM

In 1997 a controversial paper estimated the total economic value of the world's ecosystems (Costanza *et al.*, 1997). The researchers considered the global value of 17 ecosystem services, including climate regulation, erosion control, waste treatment, food production, and recreation. They obtained an estimate of $33 trillion annually, which was slightly more than gross world product at the time. While the paper was criticized for its attempt to use fairly simple economic methods to reduce all ecological functions to monetary values (El Serafy, 1998; Turner *et al.*, 1998), even critics acknowledged "the article's potential to influence environmental discourse" and generate "rich methodological discussions" (Norgaard *et al.*, 1998).

In 2014, an updated version of the paper was published by many of the same authors (Costanza *et al.*, 2014), relying upon a significantly expanded database of valuation studies to determine the value per hectare for various ecosystems. The new analysis also considered that the total global area of some ecosystems had expanded since the first study, including cropland, grasslands, and deserts, while other ecosystems had declined, including forests, tundra, and coral reefs. Considering both these changes, the authors estimated the value of the world's ecosystems to be $125 trillion per year in 2011 (see Table 6.1), significantly greater than world gross product of around $75 trillion.

We can see in the table that wetlands have a particularly high value per hectare, and comprise over 20 percent of the global ecosystem value. Coastal ecosystems have a much lower value per hectare but a slightly higher global value due to their much greater area. And while open oceans have a relatively low value per hectare, they cover 64 percent of the planet, and thus also contribute a large share of the global total.

While the authors assert that their new estimates are an improvement over the 1997 study, they also note that their values are "a crude approximation at best" (p. 156). They write that the main purpose of their analysis is "to raise awareness of the importance of ecosystem services to society and serve as a powerful and essential communication tool to inform better, more balanced decisions regarding trade-offs with policies that enhance GDP but damage ecosystem services" (p. 157).

Table 6.1 The Value of the World's Ecosystems

Ecosystem	Value/Hectare/Year	Total Global Value/Year (Trillions)
Open ocean	$1,368	$21.9
Coastal	$8,944	$27.7
Tropical Forests	$5,382	$6.8
Temperate Forests	$3,137	$9.4
Grass/Rangelands	$4,166	$18.4
Wetlands	$140,174	$26.4
Lakes/Rivers	$12,512	$2.5
Desert	No value estimated	$0
Cropland	$5,567	$9.3
Urban areas	$6,661	$2.3
GLOBAL TOTAL		$124.7

Source: Costanza *et al.*, 2014.

For many nonmarket goods there is not a direct "price" that must be paid to receive benefits. Clean air, for example, is something for which many people would be willing to pay some amount of money. Let's suppose, for example, that someone living in a polluted city is willing to pay up to $200 per year for an improvement in air quality. This $200 per year represents the economic benefit they would obtain with cleaner air, similar to the concept of consumer surplus. In principle, the aggregate willingness to pay of all residents in the city could be weighed against the costs of cleaner air to determine if a policy to reduce air pollution makes economic sense.

What if a specific policy proposal would instead damage or destroy a certain environmental resource or decrease environmental quality? In situations where a policy would decrease environmental benefits, we can ask how much people would be willing to accept in compensation for these changes. This is the **willingness to accept (WTA)** approach to environmental valuation. Both WTP and WTA are theoretically correct measures of economic value. They can be applied to any potential policy situation. We will consider various economic techniques used to estimate WTP or WTA shortly, but first we turn to a discussion of the different types of economic value.

> **willingness to accept (WTA)** the minimum amount of money people would accept as compensation for an action that reduces their well-being.

Use and Nonuse Values

Economists have developed a classification scheme to describe the various types of values that we place on the environment. First, values are classified as either **use values** or **nonuse values**.[2] Use values are tangible benefits that can be physically observed. Use values are further classified into direct-use value and indirect-use value. **Direct-use value** is obtained when we make a deliberate decision to use a natural resource. These values may derive from the financial benefits that we obtain by extracting or harvesting a resource, such as the profits from drilling for oil or harvesting trees. They may also derive from the well-being that we obtain by physically interacting with a natural environment, such as fishing or going for a hike. Note that according to this classification we can obtain a direct-use benefit even if we leave a natural resource relatively untouched. So simply going for a walk in a forest would be considered a direct-use benefit.

Indirect-use values are tangible benefits obtained from nature, but without any effort on our part. Also referred to as **ecosystem services**, they include flood prevention, the mitigation of soil erosion, pollution assimilation, and pollination by bees. While these benefits may not be as apparent or tangible as direct-use benefits, they are still valid economic benefits and should be included in an economic analysis. As long as people are willing to pay something for an ecosystem service, environmental economists would count these benefits as economic values—just as "real" as the monetary benefits of harvesting timber or extracting oil.

Nonuse values are derived from the intangible well-being benefits that we obtain from the environment. While these benefits are psychological in nature, they are nonetheless "economic" as long as people are willing to pay for them. Economists have defined three types of nonuse values. First, there

> **use values** the value that people place on the tangible or physical benefits of a good or service.
>
> **nonuse values** values that people obtain without actually using a resource (i.e., psychological benefits); nonuse values include existence, option, and bequest values.
>
> **direct-use value** the value one obtains by directly using a natural resource, such as harvesting a tree or visiting a national park.
>
> **indirect-use value** ecosystem benefits that are not valued in markets, such as flood prevention and pollution absorption.
>
> **ecosystem services** beneficial services provided freely by nature such as flood protection, water purification, and soil formation.

is **option value**, or the amount that people are willing to pay to preserve a resource because they may wish to use it in the future. One example is someone's willingness to pay to ensure the protection of the Arctic National Wildlife Refuge in Alaska, which provides habitat for caribou, wolves, and other species, because he or she might visit it in the future. Another expression of option value would be the value placed on preservation of the Amazon rainforest because the cure for a disease might someday be discovered using one of the species found there.

option value the value that people place on the maintenance of future options for resource use.

bequest value the value that people place on the knowledge that a resource will be available for future generations.

existence value the value people place on a resource that they do not intend to ever use, such as the benefit that one obtains from knowing an area of rain forest is preserved even though he or she will never visit it.

The second type of nonuse value is **bequest value**, or the value that one places on a resource because he or she wishes it to be available for future generations. For example, one might wish to have the Arctic National Wildlife Refuge preserved so that his or her children will be able to visit it. Thus while option value is derived from the benefits individuals may obtain in the future, bequest values are based upon one's concern for future generations.

Finally, there is **existence value**, the benefit that an individual obtains from simply knowing that a natural resource exists, assuming that he or she will never physically use or visit the resource, and separate from any bequest value. Again, as long as someone is willing to pay for the existence of a resource, it is a valid economic benefit. Someone may be willing to pay for the preservation of the Arctic National Wildlife Refuge simply because they obtain some satisfaction knowing that such an unspoiled wilderness exists. Or consider the decrease in welfare that many people experience as a result of knowing that a pristine coastal environment has been damaged by an oil spill. From an economic perspective, these losses are just as valid as, and may even be larger than, the spill's impact on commercial fishing—even if the individuals involved never personally visit the affected area.

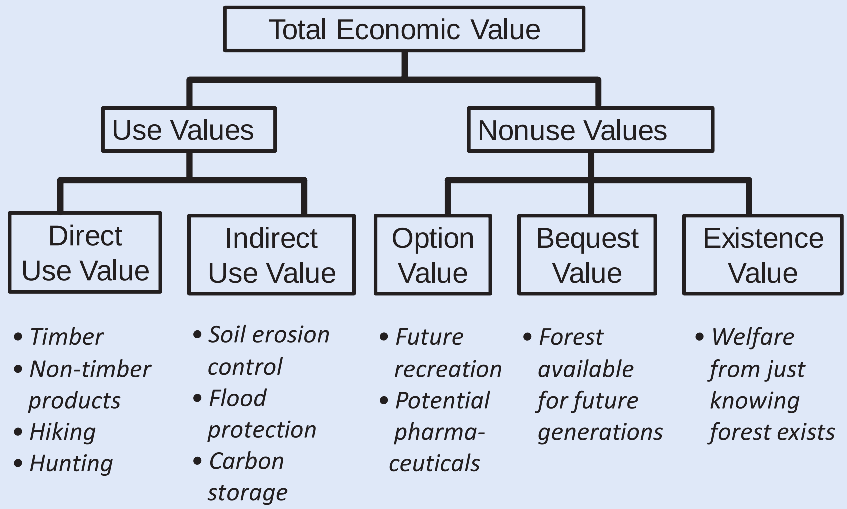
Summary of Economic Values

Figure 6.1 summarizes the different types of economic values, using a forest as an example. Note that direct-use values can include extractive uses, such as harvesting timber and non-timber products, as well as non-extractive uses, such as hiking or bird watching. Indirect-use values for a forest include the protection trees provide by reducing soil erosion, flood control, and their ability to store carbon to limit climate change. Option values can include future recreation benefits as well as the possibility that forest products may provide a source for drugs to treat diseases. A forest may also provide existence and bequest values, especially well-known forests such as the Amazon rainforest or the sequoias in California.

It is important to note that the various types of economic values we have discussed are additive. Thus the **total economic value** of a resource is simply the sum of the different use and nonuse values. Some types of values may not be relevant for a particular resource. For example, a small local park may not have any measurable existence value. But the total economic value of a major National Park is likely to include every type of value presented in Figure 6.1. Also, the total economic value of a natural resource may differ depending on how the resource is managed. For example, after harvesting trees from a forest, its indirect-use and existence benefits may decrease. If we can obtain estimates of all the different economic values under different management scenarios, in principle we could determine which scenario provides the greatest economic benefits.

total economic value the value of a resource considering both use and nonuse values.

Figure 6.1 Components of Total Economic Value



We have already seen one example in which information regarding total economic value is needed—the internalization of externalities from Chapter 3. In order to set the "correct" price of a resource that generates externalities, we need to estimate these externalities in monetary terms. The valuation of externalities applies to a situation in which a particular good or service has market value to begin with, and we need to add or subtract the value of external costs or benefits. Externalities may involve changes to both use and nonuse values. For example, the negative externalities of oil drilling include the lost ecological services from habitat degradation as well as potential loss of existence values.

cost-benefit analysis (CBA) a tool for policy analysis that attempts to monetize all the costs and benefits of a proposed action to determine the net benefit.

Another application of environmental valuation is the analysis of existing or proposed policies, which often involves assessing nonmarket values. Examples would include a proposal to establish a new National Park or a regulation that restricts use of a particular chemical. In such cases, we can use valuation techniques to develop a **cost-benefit analysis (CBA)** of the proposed policy. We will study cost-benefit analysis in the next chapter. For the remainder of this chapter, we will review the techniques that economists use to measure economic values.

6.2 OVERVIEW OF VALUATION TECHNIQUES

We can classify environmental valuation techniques into five basic categories:[3]

1. Market Valuation
2. Cost of Illness Method
3. Replacement Cost Methods

4. Revealed Preference Methods
5. Stated Preference Methods

We have already discussed how markets can be used to determine economic values in Chapter 3. Many environmental goods, such as forests, fish stocks, minerals, and groundwater, can be sold in existing markets. By estimating consumer and producer surplus, economists can calculate the benefits of these resources as market commodities—a type of direct-use value. In the case of producer surplus, the benefits are direct financial gains to the producers. In the case of consumer surplus, the benefits represent increases in welfare.

Environment impacts often include damages to human health. The **cost of illness method** monetizes the direct and indirect costs associated with illnesses attributed to environmental factors. The direct costs include medical costs, such as office visits and medication, paid by individuals and insurers, and lost wages due to illness. Indirect costs include decreases in human capital, such as when a child misses a significant number of school days due to illness and falls behind other students. Other indirect costs include the well-being losses from pain and suffering, and decreases in economic productivity due to the physical or mental effects of an illness.

cost of illness method an approach for valuing the negative impacts of pollution by estimating the cost of treating illnesses caused by the pollutant.

The direct costs associated with illnesses tend to be much easier for economists to estimate than the indirect costs. Cost of illness studies that exclude estimates of indirect costs, or some types of direct costs, thus would provide us with a lower-bound estimate of the willingness to pay to avoid these illnesses. The true maximum WTP could be greater, since direct costs may not capture the full losses to individuals from illness. But even a lower-bound estimate could provide important policy guidance about the benefits of reduced incidence of illnesses.

For example, a 2011 study estimated the cost of asthma in the United States at $56 billion per year.[4] The study estimated the incremental medical expenses for an individual with asthma to average over $3,000 per year, including prescription medication, office visits, and emergency room visits. Workers with asthma missed about three additional days of work per year, and lost productivity was calculated based on average wages for these workers. The study also valued lost days of school by assuming that an adult would need to stay home to care for an ill child, and this adult's time was also valued based on data on average wages. Finally, the damages from asthma deaths were valued based on expected lifetime economic productivity (we'll consider the valuation of human mortality in more detail in the next chapter). But note that the study did not estimate any damage from pain and suffering, or any additional impacts on affected children. Still, the aggregate value of $56 billion per year can be used as a lower-bound estimate of the potential social benefits of policies to lower asthma rates.

Replacement cost methods can be used to estimate the indirect use value of ecosystem services. These approaches consider the costs of actions that provide human-made substitutes for lost ecosystem services. For example, a community could construct a water treatment plant to make up for the lost water purification benefits from a forest habitat. The natural pollination of plants by bees could, to some extent, be done by hand or machine. If we can estimate the costs of these substitute actions, in terms of construction and labor costs, these can be considered an approximation of society's WTP for these ecosystem services.

replacement cost methods an approach to measuring environmental damages that estimates the costs necessary to restore or replace the resource, such as applying fertilizer to restore soil fertility.

A 2012 paper used the replacement cost approach to value the nutrient retention benefits of restoring a wetland in Germany.[5] Wetlands help retain soil sediments and nutrients such as nitrogen and phosphorus that otherwise flow into drinking water supplies and reduce water quality, requiring increased water treatment costs. By estimating the cost of various water treatment options, the study was able to estimate the cost savings associated with restoring the wetland. Another application of the replacement cost approach was a 2014 paper that estimated the value of water resources in the Netherlands.[6] In valuing groundwater, the analysis concluded that the best substitute would be to use desalination to obtain water of comparable quality.

In situations where multiple replacement alternatives are available, the least-cost option should be used as the basis for the replacement cost estimates. This is because if society were to lose the ecosystem service being studied, it would presumably prefer the least-cost replacement option. Another important point is that potential replacement costs are not necessarily measures of WTA or WTP. Suppose that a community could construct a water treatment plant for $50 million to offset a hypothetical loss of forest land. This estimate does not tell us whether the community would actually be willing to pay the $50 million should the forest loss occur. Actual WTP could be greater or less than $50 million and is essentially unrelated to the cost of the water purification plant. So in this sense, replacement costs should be used with caution. However, if we know that the community would be willing to pay the $50 million cost for the plant, then we could conclude that $50 million represents a lower bound of the value of the water purification benefits of the forest. But if the community would not choose to pay $50 million for the water treatment plant, then we would conclude that its value of the ecosystem purification benefits is less than $50 million.

One replacement cost method that has been used often in recent years is **habitat equivalency analysis (HEA)**. HEA is commonly applied to estimate the economic damages of accidental releases of hazardous chemicals, such as oil spills.[7] An oil spill reduces the ecological functioning of natural habitats (a loss of indirect-use benefits) until they eventually recover to baseline conditions. Under existing U.S. legislation, the responsible parties must provide compensation in terms of funding for ecological restoration. Thus the objective of HEA is to determine the appropriate amount of ecological restoration to offset the ecological losses from the accident.

The two remaining valuation methods—revealed preference and stated preference—are the most studied techniques of environmental valuation. **Revealed preference methods** indirectly infer the values that people place on environmental goods or services based on market decisions. For example, as we see in more detail below, the value that people place on clean drinking water can be inferred from the amount that they spend on bottled water.

With **stated preference methods** we use surveys to ask people their preferences for hypothetical scenarios regarding environmental quality or natural resource levels. The main advantage of stated preference methods is that we can survey people about any type of value shown in Figure 6.1. Thus an estimate of total economic value can theoretically be obtained using stated preference approaches. With revealed preference methods, we typically can only estimate one particular type of value. The main disadvantage of stated preference methods is that there are concerns about the validity of the estimates. We first consider the different types of revealed preference approaches, and then focus on stated preference methods.

habitat equivalency analysis (HEA) a method used to compensate for the damages from a natural resource injury with an equivalent amount of habitat restoration.

revealed preference methods methods of economic valuation based on market behaviors, including travel cost models, hedonic pricing, and the defensive expenditures approach.

stated preference methods economic valuation methods based on survey responses to hypothetical scenarios, including contingent valuation and contingent ranking.

6.3 REVEALED PREFERENCE METHODS

Market decisions are based on many considerations, including environmental quality. Thus even if an environmental good or service is not directly traded in a market, it may be a relevant factor for decisions made in related markets. Economists have come up with various techniques to extract meaningful valuation information from existing markets. We now take a look at the three most common revealed preference methods.

Travel Cost Models

Travel cost models (TCMs) can be used to estimate the use value of natural recreation sites, such as National Parks, beaches, and wilderness areas. Visitors to recreation sites typically must pay various trip costs such as gas and other vehicle costs (if they drive), other transportation costs such as air fares and public transportation, entrance fees, lodging, food, and so on. Assuming that visitors are behaving rationally, we can conclude that their actual visitation expenditures represent a lower bound to their maximum willingness to pay to visit the site. For example, if an individual spends $300 for a week-long camping visit to a National Park, then her maximum willingness to pay must be at least $300 because we actually observe her paying $300.

travel cost models (TCMs) use statistical analysis to determine people's willingness to pay to visit a natural resource such as a national park or river; a demand curve for the resource is obtained by analyzing the relationship between visitation choices and travel costs.

While potentially useful, data on actual expenditures do not capture consumer surplus—the true measure of net economic benefits. In order to estimate consumer surplus, we need an estimate of how the quantity demanded varies with price. The key insight of TCMs is to note that the cost to travel to a park varies for different visitors primarily based on their distance from it. Those who live nearby face relatively low travel costs, while those who travel from far away must pay higher travel costs to visit the site. This effectively provides us with variation in the "price" that different visitors must pay in order to visit a particular site. We can use this variation to estimate a full demand curve and thus obtain an estimate of consumer surplus.

One type of travel cost model is called a zonal model.[8] With a zonal TCM, we first divide up the area around one or more recreation sites into different zones. These zones are normally defined based on standard geographic divisions, such as counties, zip codes, or townships. Then we need information on visitation rates to the recreation site(s) from the various zones. We can collect this information either by surveying visitors on-site and asking them their origin or by conducting a general population survey. In a general population survey people are contacted randomly, normally by phone or mail, and asked to report on their visitation patterns to one or more recreation sites over a period, such as the past year. In either an on-site or general population survey, we ask various other questions, such as how many people they traveled with, how much they spent, length of stay, the activities undertaken during the visit, and demographic data such as age and income level.

The survey data are used to estimate how many people visited the site, or several sites in the case of a multisite model, from each origin zone. Dividing the estimate of total visits by the zonal population produces visitation per capita, which controls for differences in population across zones. This variable is used as the dependent variable in a statistical model. The primary independent, or explanatory, variable is the travel cost from each origin zone to each destination site. Travel costs can be measured using software that estimate driving distances and costs. Normally, the cost of travel time is also included, assuming that travel time is another "cost" that must be paid in order to visit a site. The cost of travel time is normally estimated as a function of the wage rate of visitors. This may be based on self-reported survey data on income or the average wage rate for a zone.

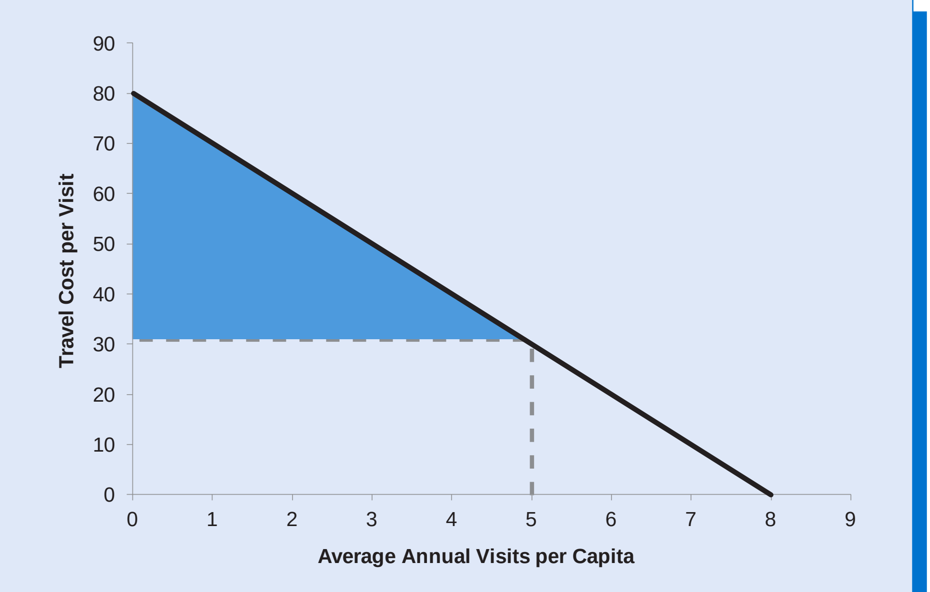
In order to estimate a robust statistical model, zonal TCMs include other independent variables besides travel cost. These include:

- Zone demographics such as age levels, family size, and income levels
- Site characteristics (for a multisite model) such as facility levels and the presence of different amenities
- Quantity and quality of substitute sites—a zone with nearby, high-quality substitutes would be expected to have lower visitation rates to a particular recreation site, *ceteris paribus*
- Other pertinent variables, such as weather conditions and the timing of weekends and holidays

The model is estimated statistically, with a negative coefficient on the travel cost variable indicating that visitation rates go down as travel costs increase—essentially a standard downward-sloping demand curve. Using the estimated model, one can then plot the demand curve by calculating expected visitation rates at different travel costs. Figure 6.2 illustrates an example showing the demand curve for a natural recreation site.[9] Suppose that for a particular zone, the average cost to visit the site is \$30. Inserting a cost of \$30 into the estimated model results in an estimated visitation rate of 5 annual visits per capita, as shown in Figure 6.2. We can then estimate consumer surplus as the area below the demand curve and above the cost of a visit—the shaded area in the figure. In this case, consumer surplus is a triangle with a base of 5 visits and a height of \$50 (the difference between the *y*-axis intercept of \$80 and the cost of \$30 per visit). So consumer surplus (CS) is:

$$CS = \tfrac{1}{2} * 5 * 50 = \$125.$$

Figure 6.2 Travel Cost Demand Curve Example



Note that this is the consumer surplus for five trips. The consumer surplus for an individual trip would be $25 ($125 divided by 5). If we had an estimate of the total number of trips from this zone, we could then estimate the total consumer surplus. The benefits to other zones could be obtained using the same approach, and then these benefits could be aggregated to obtain the total consumer surplus for the site, or the average consumer surplus per visitor.

Numerous TCMs have estimated the recreational benefits of natural sites. For example, a study of recreational visitors to the Murray River in Australia found that the average visitor received a consumer surplus of US$155 per day.[10] Another study found that the consumer surplus from visiting a National Park in Greece ranged from US$170 to US$350 per visit.[11] TCMs have been used to explore how changes in the fish catch rate affect the consumer surplus of anglers visiting sites in Wisconsin,[12] how a drought affects the benefits of visitors to reservoirs in California,[13] and how climate change will impact recreational benefits in Europe.[14]

Given that TCMs are based on actual market decisions about recreation choices, the estimates are considered relatively valid. Perhaps the main limitation of TCMs is that they can only estimate recreational use values. A TCM cannot provide the total economic value for a natural area because it cannot estimate indirect use or nonuse benefits.

Also, like any statistical model, the results of a TCM can vary considerably based on the model's structure and assumptions. For example, how a researcher values travel time can influence the resulting consumer surplus estimates. In a **meta-analysis** of 25 different TCMs that estimated forest recreation benefits in Europe, consumer surplus ranged from less than $1 to over $100 per trip.[15] This demonstrates that the results from one study are rarely directly transferable to a different situation—an issue we discuss further in the chapter.

> **meta-analysis** an analysis method based on a quantitative review of numerous existing research studies to identify the factors that produce differences in results across studies.

Hedonic Pricing

The second revealed preference method is based on the idea that environmental quality can affect the market prices of certain goods and services. **Hedonic pricing** attempts to relate the price of a marketed good to its underlying characteristics. The most common environmental application of hedonic pricing involves studying residential housing prices.

The price of a house is determined by characteristics of the property and community, such as the number of bedrooms, square footage, quality of the school system, and proximity to public transportation. Housing prices may also be affected by environmental quality or natural resource variables, including air quality, visibility, noise pollution, and proximity to a natural area. Using statistical methods, a researcher can attempt to isolate the relationship between housing prices and these environmental variables. The results indicate how much buyers are willing to pay for improved environmental quality, holding the other characteristics of the house constant.

A hedonic pricing model is typically based on analysis of a large number of home sales. Public data are available on sale prices and some property characteristics. The researcher supplements this with information on the environmental variable(s) of interest. The statistical model then determines whether there is a significant relationship between the environmental quality variable(s) and the selling price.

> **hedonic pricing** the use of statistical analysis to explain the price of a good or service as a function of several components, such as explaining the price of a home as a function of the number of rooms, the caliber of local schools, and the surrounding air quality.

Box 6.2
DO WIND TURBINES REDUCE LOCAL PROPERTY VALUES?

As we will discuss in Chapter 11, wind power is one of the fastest growing sources of energy. However, opponents of new wind turbines often claim that views of turbines reduce property values. For example, in the debate about constructing a large wind farm off the coast of Cape Cod, Massachusetts, many local residents believed that the presence of over 100 turbines, each more than 400 feet tall, about five miles offshore would reduce the quality of ocean views, and thus lower property values.

Hedonic pricing can clearly help determine whether wind turbines actually do reduce property values.

A 2015 study provides one of the most comprehensive analyses of the issue (Hoen *et al.*). The researchers collected a dataset of over 50,000 home sales in 27 U.S. counties with wind turbines, which included about 1,200 houses that were located within one mile of a turbine. They not only considered whether existing turbines reduced property values, but also whether there was an impact of announcing the construction of a new turbine. Their results indicate that "across all model specifications, we find no statistical evidence that home prices near wind turbines were affected in either the post-construction or post-announcement/pre-construction periods. Therefore, if effects do exist, either the average impacts are relatively small and/or sporadic" (p. 48). Further, they indicate that their conclusion is consistent with the majority of other hedonic analyses on wind turbines, which also find that wind facilities "produce little or no effect on home values" (p. 48).

The results from hedonic models have been mixed.[16] In some hedonic models studying the effects of local air quality on real estate prices, no statistically significant relationship was found. But other studies conclude that real estate prices are positively correlated with better air quality. A study based on data from 242 metropolitan areas in the United States found that the marginal willingness to pay for a 1 $\mu g/m^3$ reduction in particulate matter concentration was \$148–\$185.[17]

A 2015 hedonic study determined that proximity to a national or state park increased property values in Colorado, while proximity to a national forest had no significant impact.[18] Another 2015 study found that apartment sale prices in Vienna, Austria, increased the closer they were to the city's greenbelt.[19] Other research has found that homes located near hazardous waste sites or sources of noise, such as airports and highways, are associated with lower prices, *ceteris paribus*. A 2010 meta-analysis found that high-volume landfills (500 tons per day or more) decrease property values by an average of 14 percent, while low-volume landfills decrease property values by only 3 percent.[20] See Box 6.2 for another example of hedonic pricing.

The Defensive Expenditures Approach

In some cases, individuals may be able to reduce or eliminate their exposure to environmental harms by buying certain consumer goods or taking other actions. For example, households with concerns about their drinking water quality may purchase bottled water, install a home water purification system, or obtain their drinking water from another source. Exposure to air pollutants can be reduced by purchasing home air purifiers. If we observe individuals spending money or time for environmental quality improvements, then we can use this information to infer the WTP for quality changes.

The **defensive expenditures approach** collects data on actual expenditures to obtain a lower-bound WTP for environmental quality changes.[21] The most common application of the defensive expenditures approach is to drinking water quality. The premise is that if a household is observed paying, say, $20 per month for bottled water in response to concerns about the quality of their tap water, then their WTP for an improvement in drinking water quality is at least $20 per month.

defensive expenditures approach a pollution valuation methodology based on the expenditures households take to avoid or mitigate their exposure to a pollutant.

For example, one study surveyed households in Pennsylvania to identify the actions that they were taking in response to a municipal water contamination incident.[22] Defensive expenditures in the community during the incident ranged from about $60,000 to $130,000, depending on how time was valued. As a lower-bound estimate of the WTP to avoid similar contamination incidents, the results can indicate whether investments to safeguard municipal water supplies are economically efficient.

An analysis in Brazil found that households were paying $16–$19 per month on defensive expenditures to improve drinking water quality.[23] In this study, 79 percent of households were taking some measures to improve the quality of the water that they drink. Given concerns about drinking water quality in developing countries, the defensive expenditures approach provides a means for estimating the benefits of better access to safe drinking water.

One limitation of the defensive expenditures approach is that it only provides a lower-bound estimate to WTP. A household may be willing to spend much more than it actually is spending to improve the quality of its drinking water, but this approach does not allow us to estimate its maximum WTP. Another potential problem with the defensive expenditures approach is that individuals who take actions to reduce their exposure to environmental harms may also be taking such actions for other reasons.[24] For example, someone who buys bottled water for a perceived improvement in water quality may also be motivated by its convenience or taste. In this case, only a portion of one's defensive expenditures should be attributed to a desire for better water quality, meaning that defensive expenditures could overestimate the true WTP for better water quality. To reduce this problem, a researcher would need to identify expenditures made solely to reduce environmental exposure.

6.4 STATED PREFERENCE METHODS

While revealed preference methods have the advantage of being based on actual market decisions, these methods are applicable only in certain situations (e.g., hedonic models mainly estimate environmental characteristics that affect housing prices) and only to obtain use benefits. Revealed preference methods cannot be used to obtain estimates of nonuse benefits, so they normally do not reveal the total economic value of a natural resource. Stated preference methods, in contrast, can be applied to any situation to determine the WTA or WTP for a hypothetical scenario. Using a survey, we can ask respondents about the total economic value that they place on a resource, including use and nonuse benefits.

contingent valuation (CV) an economic tool that uses surveys to question people regarding their willingness to pay for a good, such as the preservation of hiking opportunities or air quality.

The most common stated preference method is **contingent valuation (CV)**.[25] The name indicates that a respondent's valuation is contingent on that person's reaction to a hypothetical scenario presented in a survey format. CV questions can be phrased in terms of either WTA, for a scenario that decreases utility, or WTP, for a scenario that increases utility. So a researcher could ask respondents what minimum amount they would accept as compensation for a 10 percent decrease in air quality or what maximum amount they would pay for a 10 percent increase in air quality. In theory, for a marginal (i.e., small)

endowment effect the concept that people tend to place high value on something after they already possess it, relative to its value before they possess it.

change in environmental quality WTA and WTP should be rather similar. However, in practice WTA tends to be much larger than WTP—by an average of seven times according to one meta-analysis.[26]

You can imagine that a WTA question asking people how much money they would need for compensation creates an incentive for them to overstate that value. This divergence is one reason that some critics question the validity of contingent valuation estimates. However, the divergence may illustrate the **endowment effect**, in which people evaluate gains and losses differently. After someone already possesses something, such as a physical good or a certain level of air quality, their utility or level of satisfaction decreases significantly if it is taken away from them, because the person believes that he has established a right to it. Thus a loss from a baseline situation is viewed in a fundamentally different light than a gain from baseline.

Designing Contingent Valuation Surveys

In addition to deciding whether a CV question will be phrased in terms of WTP or WTA, there are many other details to consider when designing CV questions. There are several basic ways to ask contingent valuation questions, as illustrated in Figure 6.3 using an example of wetlands preservation:

- Open-ended: Perhaps the simplest form of CV question is the open-ended format, in which a respondent is directly asked to state a maximum WTP for a desirable scenario. Thus the respondent can offer any monetary value as their answer.
- Payment card: The respondent is presented with numerous potential WTP amounts and picks the one that most closely represents her maximum WTP.
- Single-bounded: The respondent is given a single WTP amount and asked whether he would be willing to pay this amount for the scenario being studied. The WTP amount is not the same for all respondents—a range is used to provide variation and more precisely estimate average WTP. An "unsure" option may be given to allow for uncertainty. If the question is phrased as a vote on a hypothetical ballot issue, it is called a referendum format.
- Double-bounded: A limitation of the single-bounded format is that we only know whether a respondent's WTP is above or below a certain amount. In a double-bounded question, the initial WTP amount is followed by a second question with a different WTP amount, as shown in Figure 6.3. This format provides more precise information about someone's WTP.
- Multiple-bounded: Even more precise information can be obtained using the multiple-bounded format, which asks respondents to indicate whether they would be willing to pay several different amounts.

referendum format a contingent valuation question format where the valuation question is presented as a vote on a hypothetical referendum.

strategic bias/strategic behavior the tendency for people to state their preferences or values inaccurately in order to influence policy decisions.

So which question format is preferred? CV questions have several potential sources of bias, so we can consider how each format reduces or exacerbates biases. One bias common in CV questions is **strategic bias**—when a respondent intentionally provides an incorrect WTP amount in order to advance a particular policy outcome. For example, a single-bounded question might ask a respondent whether she is willing to pay $100 per year to support protection

Figure 6.3 Contingent Valuation Question Formats

Open-Ended Format:
What is the maximum amount you would be willing to pay annually, as a tax surcharge, to fund a wetlands protection program?

Payment Card Format:
Which of the amounts below most closely indicates your maximum willingness to pay annually, as a tax surcharge, for a wetlands protection program? Please circle your answer.

$5	$40	$80	$200	$750
$10	$50	$100	$300	$1,000
$20	$60	$125	$400	$1,500
$30	$75	$150	$500	$2,000

Single-Bounded Format:
Would you be willing to pay $75 annually, as a tax surcharge, to fund a wetlands protection program?

Yes
No
Unsure

Double-Bounded Format:
Would you be willing to pay $75 annually, as a tax surcharge, to fund a wetlands protection program?

- If respondent answers "Yes," then ask: "Would you be willing to pay $150?"
- If respondent answers "No," then ask: "Would you be willing to pay $40?"

Multiple-Bounded Format:
For each dollar amount below, indicate whether you would be willing to pay that amount annually, as a tax surcharge, to fund a wetlands protection program?

$5	Yes	No	Unsure
$10	Yes	No	Unsure
$25	Yes	No	Unsure
$50	Yes	No	Unsure
$75	Yes	No	Unsure
$100	Yes	No	Unsure
$200	Yes	No	Unsure
$300	Yes	No	Unsure
$500	Yes	No	Unsure
$1,000	Yes	No	Unsure

of endangered species. Even though she actually would not pay this amount, she might answer "yes" because she basically supports protection of endangered species.

Another bias is **yea-saying**—when a respondent agrees to pay the indicated amount because he perceives it as a "correct" answer or the answer that the researcher wants to hear. Thus yea-saying will result in an upward bias to WTP amounts. **Range bias** can be a problem with the payment card and multiple-bounded formats. This is when the respondent's answers are influenced by the range of values presented. In particular, respondents may be biased to give a WTP amount in the middle of a given range of values.[27]

While most biases lead to overestimates of WTP, **protest bids** occur when someone states that he is not willing to pay for something because he thinks that he already pays enough in taxes, or objects to the question for another reason. Protest bids can be identified by including follow-up questions that ask respondents why they responded the way they did to the valuation question. Another potential bias that can be a problem with any survey is **non-response bias**—when those who respond to a survey are not representative of the population under study. If non-response bias is present, the survey results cannot be extrapolated to the entire population. Assuming a survey sample is randomly chosen, the potential for non-response bias can be minimized by obtaining a relatively

yea-saying responding "yes" to a contingent valuation WTP question even though one's true valuation of the scenario is less, for reasons such as perceiving "yes" to be a correct answer.

range bias a potential bias with payment card or multiple-bounded contingent valuation questions whereby the responses are influenced by the range of values presented to the respondent.

protest bids responses to contingent valuation questions based on the respondent's opposition to the question or the payment vehicle, rather than the underlying valuation of the resource.

high survey response rate. A meta-analysis of CV studies that value the benefits of endangered species preservation indicates that response rates of 60 percent or more can be obtained with CV surveys.[28]

non-response bias bias as a result of survey respondents not being representative of survey non-respondents.

Another issue in designing a CV survey is how it is administered to respondents. CV surveys can be administered by mail, phone, in person, or over the Internet. While Internet surveys are the cheapest to administer, they typically suffer from low response rates and are unlikely to produce representative results.[29] In-person surveys allow researchers to present detailed valuation scenarios, answer questions, and generally foster more focus on the survey questions, but they are normally the most expensive to administer. With phone and mail surveys response rates can be increased through follow-up contacts, such as continuing to call someone who does not answer with a phone survey, or multiple mailings with a mail survey.

The Validity of Contingent Valuation

Hundreds of contingent valuation studies have been conducted over the past several decades.[30] Table 6.1 provides a sampling of some of the results of recent CV analyses. We can see that CV has been applied to various environmental issues all over the world. See Box 6.3 for a discussion of one of these studies.

Despite such voluminous research, fundamental concerns about the validity of CV questions remain. A classic article whose title begins with "Ask a Silly Question . . ." concludes that "CV measurements of nonuse values are so speculative that the costs of using CV to assess damages to natural resources almost always outweigh the benefits."[31] Other researchers "conclude that many of the alleged problems with CV can be resolved by careful study design and implementation."[32] While the debate about CV's validity was initially limited to academic discussion, the 1989 *Exxon Valdez* oil spill in Alaska brought the CV debate under wider scrutiny.[33]

While some of the damages from the *Exxon Valdez* oil spill were lost use values, such as lost commercial fishing profits and recreation benefits, the federal government and the state of Alaska argued that Exxon should also compensate the public for lost nonuse values. Thus a large-scale CV survey was funded to determine the nonuse damages of the spill to the country.[34] The results estimated the total lost nonuse values at around $3 billion, significantly more than the claimed lost use value. Thus the validity of CV results suddenly became central to the damage claim being made by the government against Exxon.

To explore the validity of CV questions, the National Oceanic and Atmospheric Administration (NOAA) assembled a panel of prestigious economists, including two Nobel Prize winners, to report on the validity of the technique. After reviewing the CV literature and hearing testimony from many economists, the NOAA panel concluded that

> CV studies can produce estimates reliable enough to be the starting point of a judicial process of damage assessment, including lost passive-use values. To be acceptable for this purpose, such studies should follow the guidelines described in [the NOAA panel report]. The phrase "be the starting point" is meant to emphasize that the Panel does not suggest that CV estimates can be taken as automatically defining the range of compensable damages within narrow limits. [CV studies contain] information that judges and juries will wish to use, in combination with other evidence, including the testimony of expert witnesses.[35]

Table 6.2 Sample of Recent Environmental Contingent Valuation Results

Good or Service Valued	Average WTP Estimate(s), U.S. Dollars
Improved drinking water quality in China (1)	$3/month
Preservation of agricultural genetic diversity in Finland (2)	$54/year
Water purification filters in Kenya (3)	$17–$27 (one-time payment)
Price premium for shirts made with organic cotton in Sweden (4)	$9/shirt
Protection of endangered owls in the United States (5)	$55–$60/year
Reduced highway noise and air pollution in Spain (6)	$22/year
Increased biodiversity in Hungary (7)	$23–$69/year
Increased supplies of renewable energy in the United States (8)	$10–$27/month
Increased forest reserves in Norway (9)	$261–$303 (one-time payment)
Increased marine biodiversity in the Azores islands (10)	$121–$837 (one-time payment)

Sources: 1. Jianjun *et al.*, 2016; 2. Brouwer *et al.*, 2015; 3. Tienhaara *et al.*, 2015; 4. Fackle-Fornius and Wänström, 2014; 5. Loomis and Mueller, 2013; 6. Lera-Lopez *et al.*, 2012; 7. Szabó, 2011; 8. Mozumder *et al.*, 2011; 9. Lindhjem and Navrud, 2011; 10. Ressurreição *et al.*, 2011.

Note: WTP = willingness to pay. Some monetary values were converted to U.S. dollars based on market exchange rates.

While the NOAA panel concluded that CV studies may produce valid estimates of non-use values, it also provided a long list of recommendations in order for a CV survey to be considered acceptable, including:

- In-person surveys are preferred because they best maintain a respondent's concentration and allow for the use of graphics.
- WTP questions are preferred over WTA questions in order to avoid unrealistically high answers.
- The WTP question should be phrased using a "Yes/No" format with a specific price. For example, a question might ask whether the respondent is willing to pay $20 per year to preserve endangered species. The Yes/No format with a single price aligns with actual consumer decisions about whether to buy something. Rarely must consumers actually think about their maximum WTP.
- The sensitivity of WTP to the scope of the damage should be explored. One CV study used separate survey versions to elicit respondent's WTP to protect 2,000, 20,000, or 200,000 migratory birds from oil spills.[36] The WTP amounts were insensitive to the number of birds protected, leading the authors to conclude that CV results are not valid.
- Follow-up questions should be included to determine whether respondents understood the hypothetical scenario and why they answered the valuation question as they did.
- The respondents should be reminded of their income constraints and that funds used for the scenario under study cannot be used for other purposes.

The NOAA panel recognized the "likely tendency to exaggerate willingness to pay" in CV surveys and thus its recommendations tend to produce conservative WTP estimates "as a partial or totally offset" to this bias. In practice, very few CV surveys follow all the

Box 6.3
WILLINGNESS TO PAY FOR RENEWABLE ENERGY

At least 66 countries and 29 U.S. states have set targets for the percentage of energy that they obtain from renewable sources. For example, Germany has set an ambitious goal of obtaining 100 percent of its electricity from renewable sources by 2050. To determine the effects of such targets on social welfare, it is necessary to identify how electricity consumers value renewable energy.

A 2011 paper used contingent valuation to determine New Mexico residents' willingness to pay for an increasing share of renewable energy in their electricity supplies. An Internet-based survey was conducted, and 367 responses were obtained (a response rate of 27 percent). Respondents were first asked an open-ended question about their willingness to pay to have 10 percent of New Mexico's energy generated from renewable sources, as an additional charge above their current electricity bill. A subsequent question asked them their additional willingness to pay for a 20 percent share from renewable sources.

The results of the survey showed that the average household was willing to pay about $10 more per month to have 10 percent of the state's energy generated from renewable sources, which represented a 14 percent increase in the typical monthly bill. The average willingness to pay for a 20 percent share was about $26 per month—a 36 percent increase in their bill.

While the results of the survey indicate a significant willingness to pay for renewable energy, the results are not necessarily representative of New Mexico residents, particularly since the survey was conducted over the Internet. The average respondent was only 25 years old and, with 15 years of schooling, was more educated than normal. So clearly, extrapolation of the results to the entire state may not be a valid use of the results. Still, the authors "hope that results from this study will offer useful insights to energy regulators, utility companies and other related agencies that can design effective mechanisms and charge appropriate premiums to support a larger share of renewable energy in the energy" (p. 1125).

Source: Mozumder *et al.*, 2011.

recommendations of the NOAA panel. Even if all the recommendations are followed, the survey's validity checks may lead the researchers to conclude that the results are not valid.

Ultimately, the debate over whether CV can provide valid estimates of nonuse values may never be settled because no real-world markets exist to test its validity explicitly. But as one article phrased it, isn't some number better than no number?[37] Nonuse values are part of total economic value and theoretically should be included in any economic analysis. And in the case of the *Exxon Valdez* oil spill, these nonuse values may exceed values that are more observable.

While estimating lost nonuse values may be necessary in legal cases, some economists believe that CV should not be used to guide environmental policies because of the methodological concerns stated above or for ethical reasons. One ethical issue is that a person's WTP in a CV survey may be a function of his ability to pay. Thus CV results, like markets in general, tend to be more responsive to the preferences of wealthier participants. Instead of "one person, one vote" CV results embody a "one dollar, one vote" principle.

Another ethical critique states that putting a price on the environment fails to address issues of rights and responsibilities.

> In essence, the economists' position is that everything has a price and that the price can be discovered by careful questioning. But for most people, some matters of rights and principles are beyond economic calculation. Setting the boundaries of the market helps to define who we are, how we want to live, and what we believe in.[38]

Some of the problems with contingent valuation can be avoided by using the technique of **contingent ranking (CR)** instead. CR is also a stated preference method, but the respondents are not asked directly about their WTP. Instead, they are presented with various scenarios and asked to rank them according to their preferences.[39]

contingent ranking (CR) a survey method in which respondents are asked to rank a list of alternatives.

For example, in a UK study, respondents were asked to rank four scenarios regarding the water quality of an urban river: the current water quality, a small improvement, a medium improvement, and a large improvement.[40] Maintaining the current water quality necessitated no tax increase, but each improvement in water quality required progressively higher tax increases. Through statistical analysis, the researchers were able to estimate the average WTP for each of the three improved water quality scenarios.

Respondents may be more comfortable with the CR format since they do not have to value a scenario explicitly. Another advantage of CR over CV is that biases such as protest bids and strategic behavior, which occur when people exaggerate their responses to promote their preferred policies, may be reduced. However, CR questions can become quite difficult when each scenario consists of several different attributes or when the number of scenarios becomes large. As with CV, the validity of CR estimates for nonuse values is difficult to establish. While economists continue to conduct research on stated preference methods, making improvements in survey design and statistical analysis, it remains unclear whether a consensus will ever be reached regarding the validity of these techniques.

Summary

According to environmental economics, the economic value of natural resources is determined by what people are willing to pay for them. This differs from an ecocentric worldview in which the environment has value derived from inherent rights. Still, total economic value comprises both use values, including direct use benefits and ecosystem services, and nonuse values, which are psychological benefits.

Economists have devised various techniques to estimate the total economic value of environmental resources. Some values can be inferred from markets, either directly or indirectly. Revealed preference methods include travel cost models, hedonic pricing, and the defensive expenditures approach. These techniques can be used to estimate the benefits of outdoor recreation, drinking water quality, air quality, and a few other environmental services. Nonuse values, often an important component of the value of natural resources, can only be measured using stated preference methods such as contingent valuation. CV uses surveys to ask respondents about their willingness to pay for environmental improvements. Contingent valuation is controversial because of potential biases that cast doubt on the validity of the method. According to a report prepared by prominent economists in the aftermath of the 1989 *Exxon Valdez* oil spill, CV studies can provide a starting point for determining economic values, but only if certain guidelines are followed. Contingent ranking provides an alternative that still uses surveys to elicit policy preferences, but avoids many of the potential biases of CV studies.

Key Terms and Concepts

bequest value
contingent ranking (CR)
contingent valuation (CV)
cost of illness method
cost-benefit analysis
defensive expenditures approach
direct-use value
ecosystem services
endowment effect
existence value
habitat equivalency analysis (HEA)
hedonic pricing
indirect-use values
meta-analysis
nonmarket benefits
nonuse values
non-response bias
option value
precautionary principle
protest bids
range bias
referendum format
replacement cost methods
revealed preference methods
stated preference methods
strategic bias/strategic behavior
total economic value
travel cost models (TCM)
use values
willingness to accept (WTA)
willingness to pay (WTP)
yea-saying

Discussion Questions

1. What are the strengths and limitations of using estimates of total economic value to develop environment policy recommendations? How does your answer relate to your worldview (anthropocentric or ecocentric)?
2. Do you think contingent valuation should be widely used as a tool for developing environmental policy recommendations? What do you think is the main strength of CV? What do you think is its main weakness?

Notes

1. See, for example, Sagoff, 2004.
2. Nonuse values are also called passive-use values.
3. These valuation techniques are classified differently by some environmental economists. In particular, Market Valuation may be classified together with Revealed Preference Methods and in some cases with Replacement Cost Methods as well. We keep the categories disaggregated to emphasize the differences among the techniques. For a more in-depth overview of environmental valuation techniques, see Ulibarri and Wellman, 1997.
4. Barnett and Nurmagambetov, 2011.
5. Grossmann, 2012.
6. Edens and Graveland, 2014.
7. Roach and Wade, 2006.

8. Another type of travel cost model is called a random utility model. Since zonal models are easier to understand, we limit our discussion here to them.
9. The figure shows a linear demand curve for simplicity. Normally, a travel cost demand curve is estimated as a nonlinear function.
10. Rolfe and Dyack, 2010.
11. Latinopoulos, 2014.
12. Murdock, 2006.
13. Ward *et al.*, 1996.
14. Barrios and Rivas, 2014.
15. Zanderson and Tol, 2009.
16. For a summary of hedonic pricing model results, see Boyle and Kiel, 2001; Palmquist and Smith, 2002.
17. Bayer *et al.*, 2009. 1 $\mu g/m^3$ is one milligram per cubic meter, a measure of pollutant levels in air.
18. Kling *et al.*, 2015.
19. Herath *et al.*, 2015.
20. Ready, 2010.
21. The defensive expenditures approach is also called the averting expenditures or averting behavior approach.
22. Abdalla *et al.*, 1992.
23. Rosado *et al.*, 2006.
24. This issue is called the "jointness in production" problem.
25. For an overview of contingent valuation, see Breedlove, 1999; Whitehead, 2006.
26. Horowitz and McConnell, 2002.
27. See Roach *et al.*, 2002, for a study that found range bias with the multiple-bounded format.
28. Richardson and Loomis, 2009.
29. See, for example, Marta-Pedroso *et al.*, 2007. They conducted a CV survey using both in-person and Internet formats. While they obtained a response rate of 84 percent for in-person contacts, the response rate for the Internet survey was only 5 percent. Mail and phone survey response rates can typically exceed 50 percent when follow-up contacts are employed.
30. A search for the term "contingent valuation" in the title of journal articles in scholarly journals results in over 700 matches, using the search engine EconLit.
31. Anonymous, 1992.
32. Carson *et al.*, 2001.
33. See Portney, 1994.
34. Carson *et al.*, 2003.
35. Arrow *et al.*, 1993.
36. Desvousges *et al.*, 1993.
37. Diamond and Hausman, 1994.
38. Ackerman and Heinzerling, 2004, p. 164.
39. A similar methodology is contingent choice, in which respondents are asked to pick one scenario from a list as their preferred option.
40. Bateman *et al.*, 2006.

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Web Sites

1. **www.rff.org.** Home page for Resources for the Future, a nonprofit organization that conducts policy and economic research on natural resource issues. Many RFF publications available on their Web site use nonmarket techniques to value environmental services.

2. **www.evri.ca/Global/HomeAnonymous.aspx.** Web site for the Environmental Valuation Reference Inventory (EVRI), developed by the government of Canada. The EVRI is a "searchable storehouse of empirical studies on the economic value of environmental benefits and human health effects. It has been developed as a tool to help policy analysts use the benefits transfer approach. Using the EVRI to do a benefits transfer is an alternative to doing new valuation research."

CHAPTER 7

Cost-Benefit Analysis

Chapter 7 Focus Questions

- How do economists conduct cost-benefit analyses?
- What are the strengths and limitations of cost-benefit analysis?
- How can we value human life and health?
- How can we value the interests of future generations?

7.1 OVERVIEW OF COST-BENEFIT ANALYSIS

One common definition of economics is that it is about the allocation of scarce resources. Like individuals and businesses, governments often have to make decisions about the allocation of limited resources. Budgetary constraints prevent us from pursuing all proposed public projects that may increase the welfare of society. How should governments decide which projects should be undertaken and which ones should be passed over? For example, should public funds be allocated to build more roads, provide health care, or improve environmental quality? Further, how should governments decide which policy proposals to enact, and which ones to reject?

The valuation techniques discussed in the previous chapter allow for a decision-making framework in which all impacts can theoretically be assessed and compared using a common metric—a monetary measure, such as dollars. **Cost-benefit analysis** (CBA) seeks to measure all the costs and all the benefits of a proposed project or policy in monetary units.[1] In principle, using a common metric makes it easier to assess tradeoffs objectively.

cost-benefit analysis (CBA) a tool for policy analysis that attempts to monetize all the costs and benefits of a proposed action to determine the net benefit.

For example, consider a federal government decision about the allowable level of ground-level ozone. Ozone is formed when pollutants such as nitrogen oxides and volatile organic compounds interact with sunlight. Breathing ozone contributes to respiratory problems such as asthma and emphysema, reduces visibility, and damages vegetation. Suppose that, compared to baseline conditions, a stricter standard would cost the country an additional $16 billion per year but prevent an estimated 5,000 premature deaths annually. Is the cost of the stricter standard worth it? In other words, is the benefit of 5,000 avoided deaths worth the cost of $16 billion per year? (See Box 7.1 for an answer to this real-world question.) CBA provides one tool for helping us make such decisions. In fact, under existing U.S. law, federal agencies, including the Environmental Protection Agency, are required to conduct CBAs for major policy proposals, as we'll discuss later in the chapter.

The basic steps of a CBA seem rather straightforward:

1. List all the costs and benefits one can think of in relation to a proposed action.
2. For costs and benefits ordinarily measured in monetary units, obtain reliable estimates.
3. For costs and benefits not ordinarily measured in monetary units, such as human health or ecosystem impacts, use nonmarket valuation techniques to obtain estimates.
4. If actual nonmarket values cannot be estimated due to budgetary or other constraints, consider transferred values or expert opinions.
5. Add up all the costs and all the benefits, preferably under a range of plausible assumptions or scenarios.
6. Compare total costs to total benefits to obtain a recommendation.

CBAs normally consider various alternatives, including a baseline or "no action" option. For example, the current ozone air pollution standard might be compared to several stricter standards.

Of course, in practice CBA can be a technically difficult undertaking. In particular, estimating all nonmarket impacts in monetary units may not be feasible or even desirable. Thus most CBAs are incomplete to some extent. This does not necessarily mean that it is not possible to obtain definite policy recommendations, as we will see below.

Suppose for now that we are able to estimate all the costs and benefits of a policy proposal in monetary units. Let's say that the benefits of the ozone standard mentioned above are $24 billion per year and the costs are $16 billion per year. The bottom-line result of a CBA can be presented in two main ways:

net benefits total benefits minus total costs.

benefit/cost ratio total benefits divided by total costs.

1. **Net benefits**: This is total benefits minus total costs. In this example, net benefits are $24 billion minus $16 billion, or $8 billion. Note that if costs were greater than benefits, net benefits would be negative.
2. **Benefit/cost ratio**: This is total benefits divided by total costs. In this case, the benefit/cost ratio would be $24 billion divided by $16 billion, or 1.5. A ratio of less than 1 indicates costs greater than benefits.

Box 7.1 ENVIRONMENTAL PROTECTION AGENCY ISSUES NEW REGULATION ON OZONE POLLUTION

In October 2015 the U.S. Environmental Protection Agency announced a decision to lower the national standard for ground-level ozone from 75 to 70 parts per billion. The decision drew criticism from both industry and environmentalists. Industry was lobbying for no change to the 75 ppb standard. Jay Timmons, president of the National Association of Manufacturers, stated that the new standard was "simply overly burdensome" and would harm the U.S. economy. Similar sentiments were expressed by the American Petroleum Institute, which said that the new regulation "could be the most expensive ever."

Meanwhile, environmentalists had been advocating for an even stricter standard of 60 or 65 ppb. Frank O'Donnell, president of Clean Air Watch, responded that the new standard was merely "a baby step" and not the "giant stride" that was needed. David Baron, an attorney with Earthjustice, said the new standard "would allow thousands of deaths, hospitalizations, asthma attacks, and missed school and work days that would have been prevented by the much stronger standard supported by medical experts."

So which side's critique was more accurate? In November 2014 the EPA published a detailed cost-benefit analysis, over 500 pages long, of different ozone standards. The costs and benefits of the three proposed new standards are presented in Table 7.1. Note that while the costs are precisely estimated, the benefits vary due to uncertainty about the extent to which negative health impacts would be reduced. As we would expect, the compliance costs increase with tighter standards, from about $5 billion annually for the 70 ppb standard to over $40 billion for the 60 ppb standard. But the benefits also increase as the standard is lowered, measured both in terms of avoided deaths and monetized values. This results in a range of possible estimated net benefits for each standard level.

We see that the 70 ppb clearly provides positive net benefits relative to the old 75 ppb standard. The 65 ppb standard potentially provides even greater net benefits, although the benefit-cost ratio is likely to be slightly lower. The 60 ppb standard is the only alternative that potentially fails to provide positive net benefits (at the lower end of the estimate range), but it could also result in the highest net benefits (at the higher end of the range). So based on this cost-benefit analysis, tightening the standard from 75 to 70 ppb was economically justified. There also seems to be a legitimate argument for tightening the standard further, at least to 65 ppb. But this example illustrates the point made in this chapter that the policy recommendations of cost-benefit analyses are often ambiguous, highly dependent upon the assumptions made in the analysis.

Sources: Ambrosio, 2015; U.S. EPA, 2014.

Table 7.1 Cost-Benefit Analysis of Proposed Ozone Standards in the United States, Relative to Baseline Standard (75 ppb)

	70 ppb Standard	65 ppb Standard	60 ppb Standard
Annual Compliance Costs (billions of dollars)	$4.7	$16.6	$41.2
Annual Avoided Deaths	1,400–2,100	4,100–6,400	7,600–11,800
Annual Monetized Benefits (billions of dollars)	$7.5–$15.0	$21.2–$42.1	$37.2–$75.9
Annual Net Benefits (billions of dollars)	$2.8–$10.3	$4.6–$25.5	–$4.0–$34.7
Benefit-Cost Ratio	1.6–3.2	1.3–2.5	0.9–1.8

Source: U.S. EPA, 2014.

Note: The EPA's cost-benefit analysis separately estimated the impacts to California and the rest of the nation. Our data here combine the two sets of results, taken from Tables ES-6, ES-7, and ES-10 of the study.

If a proposal yields positive net benefits (or a benefit/cost ratio greater than 1), does this mean we should proceed with it? Not necessarily. Recall that economics is about trying to maximize net benefits. So while the ozone standard yields positive net benefits, there may well be an alternative proposal that could generate more than $24 billion in annual benefits for the same cost. We should make sure that we have considered a range of options before proceeding with a particular recommendation.

It is also important to note that a bottom-line estimate of net benefits does not tell us anything about the distribution of costs and benefits across society. Suppose that the benefits of a proposal accrue primarily to wealthy households while the costs fall on poorer households. Even though such a proposal might yield positive net benefits, we could reject it on equity grounds. Thus one should be careful about relying solely on CBA to make policy decisions, as we discuss further at the end of the chapter. But first let's consider several important issues involved in conducting a CBA.

7.2 BALANCING THE PRESENT AND FUTURE: THE DISCOUNT RATE

In most CBAs, some of the costs and benefits occur in the future. We know that a cost of $100 now is not equivalent to a cost of $100 in 10 or 20 years. This is partly due to inflation. We can control for inflation by presenting all results in **real**, or **inflation-adjusted**, **dollars**.[2] But even if the $100 value is expressed in real (inflation-adjusted) terms, the value of $100 in the future will generally not be the same as its value today.

There are a number of reasons why people may prefer a monetary benefit now rather than later. Money available now can usually be invested to get a positive real (inflation-adjusted) return. That means that $100 today will grow into, say, $200 ten years from now. In this sense, $100 today is equivalent to $200 ten years from now. Another reason for preferring money now may be uncertainty about the future—if we get the benefit now we don't have to worry about whether we will actually get it in the future. Then there is simple impatience—the natural human tendency to focus on the present more than the future.[3] So beyond adjusting for inflation, most economists believe that a further adjustment is necessary to compare present and future impacts. This adjustment is known as **discounting**.

> **real** or **inflation-adjusted dollars** monetary estimates that account for changes in price levels (i.e., inflation) over time.
>
> **discounting** the concept that costs and benefits that occur in the future should be assigned less weight (discounted) relative to current costs and benefits.

Discounting essentially "devalues" any impacts that occur in the future as less relevant than a similar impact that occurs now. Thus a $100 benefit in 10 years is not as valuable as a $100 benefit now, even if both are expressed in real terms. In other words, the $100 benefit in 10 years would be worth less than $100 now. We would use the following formula to calculate the present, or discounted, value of a future benefit or cost:

$$PV(X_n) = X_n \,/\, (1 + r)^n$$

where n is the number of years in the future the benefit or cost occurs and r represents the **discount rate**—the annual rate by which future values are reduced, expressed as a proportion (i.e., $r = 0.03$ for a 3 percent discount rate). Using this formula, at a 3 percent discount rate, a benefit (or cost) of $100 in 10 years is equivalent to getting a $74.41 benefit now. At a higher discount rate of 7 percent, a benefit (or cost) of $100 in ten years is worth only $50.83 today.

discount rate the annual rate at which future benefits or costs are discounted relative to current benefits or costs.

present value the current value of a stream of future costs or benefits; a discount rate is used to convert future costs or benefits to present values.

As you can see by the formula, the **present value** is lower the further out in time we go (since a higher exponent makes the denominator larger) or the higher the discount rate (which also makes the denominator larger). Table 7.2 and Figure 7.1 illustrate how the present value of $100 varies depending on the discount rate and the time period. The range of discount rates shown, from 1 percent to 10 percent, is typical of the ones used in economic analyses.

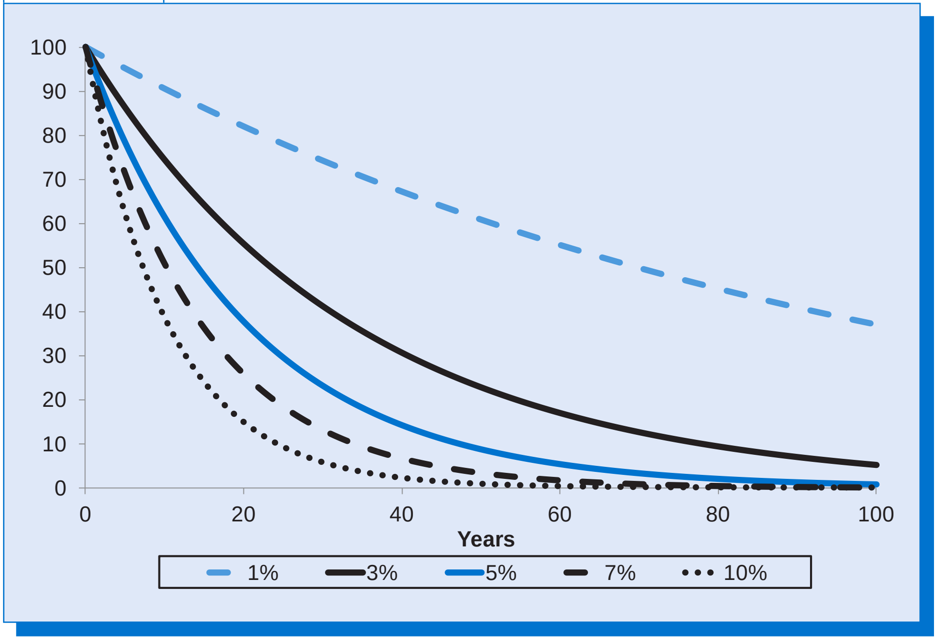
Note that the higher discount rates dramatically reduce the relevance of impacts that occur just a few decades in the future. For example, a $100 cost that occurs 50 years in the future has a present value of only $3.39 at a 7 percent discount rate and just $0.85 at a 10 percent rate. Also, small changes in the discount rate can have a dramatic effect over longer horizons. While the difference between a 1 percent and 3 percent discount rate is not that large 10 years into the future, after 100 years the present value is about seven times greater with the 1 percent discount rate.

We see in Table 7.2 that even moderate discount rates essentially render irrelevant any impacts that occur more than a few decades in the future. For example, with a 5 percent discount rate it would not be worth spending even $1 now to avoid a damage of $100 that occurs 100 years in the future.

Table 7.2 Present Value of a $100 Impact, by Discount Rate

Years into the Future	Discount Rate				
	1%	3%	5%	7%	10%
0	$100.00	$100.00	$100.00	$100.00	$100.00
10	$90.53	$74.41	$61.39	$50.83	$38.55
20	$81.95	$55.37	$37.69	$25.84	$14.86
30	$74.19	$41.20	$23.14	$13.14	$5.73
50	$60.80	$22.81	$8.72	$3.39	$0.85
100	$36.97	$5.20	$0.76	$0.12	$0.01

Figure 7.1 Present Value of a $100 Impact, by Discount Rate



Clearly, the choice of a discount rate is an important decision in any CBA. A high discount rate will highly favor the present over the future, while a low discount rate will give more weight to future costs or benefits. In many environmental applications, the benefits occur in the future while the costs are paid in the short term. Climate change is perhaps the best example of this. The costs of mitigating climate change would occur in the near term while the benefits (i.e., reduced damages) would occur decades and even centuries in the future (as discussed in detail in Chapter 12). Thus a low discount rate will generally support a higher degree of environmental protection.

So what is the "correct" discount rate? There is no clear consensus in the economics profession that one discount rate should be used in all circumstances. In fact, there are two different main approaches for determining how a discount rate should be chosen One approach to determine the discount rate is to set it equal to the rate of return on low-risk investments such as government bonds. The rationale behind this is that funds used for a beneficial public project could otherwise be invested with interest to provide society with greater resources in the future. In other words, the market rate of return represents the opportunity cost of spending money now.

By using investment rates as the discount rate in a CBA, we are evaluating the proposal relative to the opportunity cost of other investments that could be made instead. In 2016 the rates of return on medium- to long-term government bonds were 2.0–3.5 percent in nominal terms and 0.3–1.5 percent in real terms.[4]

Of course, the rates of return on government bonds vary over time. By historical standards returns were unusually low in 2016, but in the early 1980s these rates reached 13 percent in nominal terms. This leads some economists to wonder whether we should base the valuation of long-term effects upon an interest rate that is subject to the whims of financial market conditions.

A different approach to determining the discount rate is based on two justifications for discounting:

pure rate of time preference the rate of preference for obtaining benefits now as opposed to the future, independent of income level changes.

social discount rate/social rate of time preference (SRTP) a discount rate that attempts to reflect the appropriate social valuation of the future.

1. The natural human tendency to prefer the present over the future. This is known as the pure rate of time preference.
2. Assuming that real economic growth continues, people in the future will be richer than people now. So $100 in damages (in real terms) to them is "less damaging" than a $100 damage now, because it will represent a smaller share of their wealth and thus have a smaller effect on their welfare. Similarly, $100 in benefits will be less valuable to people in the future than $100 to people today, just as $100 is less important to a rich person than to a poor person. In more technical terms, utility is assumed to be a diminishing marginal function of consumption.

These two factors can be combined to estimate the **social discount rate**, or **social rate of time preference (SRTP)**, as:

$$SRTP = \rho + (\varepsilon * c),$$

where ρ is the pure rate of time preference, c is the annual growth rate of consumption, and ε is the elasticity of the marginal utility of consumption. Multiplying the growth rate of consumption by the rate at which the extra satisfaction from increased consumption declines as consumption increases (in economic terms, the elasticity of the marginal utility of consumption) tells us how much better off a society is as it gets richer.

Estimates of the historical growth rate of consumption can be obtained from government data sources. In projecting real consumption growth rates into the future, the Stern Review (a famous cost-benefit analysis of global climate change that we discuss in Chapter 12) uses a value of $c = 1.3$ percent.[5] Estimates of the value of ε are about 1.0–2.0, with one recent analysis finding a value of 1.4.[6]

A vigorous debate among economists has focused on the value of ρ. The Stern Review used a value of $\rho = 0.1$. The justification for setting the pure rate of time preference to near zero is that one generation's welfare is not inherently more important than another generation's welfare.

Thus with the Stern Review using $c = 1.3$ percent, $\varepsilon = 1.0$, and $\rho = 0.1$, a final discount rate of 1.4 percent is obtained. In another commonly referenced analysis of climate change, the value of ρ was set significantly higher at 1.5, leading to a discount rate of more than double the Stern estimate.[7] Many economic analyses use higher discount rates based on higher values for ρ and ε. The justification for these higher values of ρ and ε is that these values more closely align with the time preference implied by financial market decisions. For example, using the same value of $c = 1.3$ percent, setting $\rho = 1.5$ and $\varepsilon = 1.4$ yields a final discount rate of 3.4 percent. Compared with a 1.4 percent discount rate, using a rate of 3.4 percent will yield a present value for an impact 100 years in the future only one-seventh as large.

What do economists think the discount rate should be? In 2001 over 2,000 economists were surveyed for their opinion on "the appropriate real discount rate to be used for evaluating environmental projects over a long time horizon."[8] The average response was 4.0 percent, with a median value of 3.0 percent.

One might question whether the opinions of economists should be the ultimate factor in determining the discount rate for environmental analyses. In particular, if economists devote so much effort to asking people their preferences for environmental values using contingent valuation questions, why not also ask people their opinions regarding time preferences? In an innovative 2003 paper, Colorado residents were asked to reveal their willingness to pay to prevent future forest loss as a result of climate change. From their responses the researchers were able to imply the time preferences of respondents:

> Our estimates conclude that the public's discount rate is somewhat less than 1 percent. Interestingly, and probably not surprisingly to non-economists, the public's estimated discount rate is lower than that suggested by economists.[9]

7.3 VALUING HUMAN LIFE

Perhaps the most controversial topic in CBA is the valuing of human life. Many environmental policies, such as those setting standards for air pollution or contaminants in drinking water, affect mortality rates. Toxicological studies can provide estimates of the number of deaths that can be prevented by specific policies. Say, for example, that a policy to improve air quality would cost $500 million in terms of pollution control equipment and administrative costs but reduce the number of deaths associated with air pollution by 50 per year. Is such a policy "worth it" to society?

In one sense, we must at least implicitly value human lives when designing environmental policies. Even if it were technically feasible to eliminate all mortality associated with environmental pollution, surely the cost would be prohibitive. Thus society must make a tradeoff between mortality rates and expenditures to reduce pollution. Of course, technological improvements can always be sought to reduce exposure to harmful contaminants, but for the foreseeable future policy makers will need to determine "acceptable" standards for such contaminants, even though these levels of pollution still cause some mortality.

It is obviously unreasonable to ask someone how much he or she would be willing to pay to avoid dying from environmental pollution. Thus economists do not value any specific individual's life. Instead, economists seek to estimate how people value relatively minor changes in their risk of dying and use this information to infer the **value of a statistical life (VSL)**. A VSL estimate, in theory, indicates how much society is willing to pay to prevent one death from environmental pollution, without any specific reference to whose death will be avoided.

> **value of a statistical life (VSL)** the willingness to pay of society to avoid one death based on valuations of changes in the risk of death.

An example best illustrates how a VSL can be estimated. Suppose that we conduct a contingent valuation survey to ask people how much they would be willing to pay for a policy that would improve air quality such that the number of people who die from air pollution would be reduced by 50 per year. If we assume that the respondents to the survey are representative of the broader population, then they have just as much chance of benefiting from the policy as anyone else, on average. Suppose that the survey results indicate that the average household is willing to pay $10 per year for such a policy. If society comprises 100 million households, then the total willingness to pay for the policy would be:

$$100 \text{ million} * \$10 / \text{year} = \$1 \text{ billion}.$$

Since this is the WTP to reduce annual deaths by 50, the VSL would be:

$$\$1 \text{ billion} / 50 \text{ deaths} = \$20 \text{ million} / \text{death}.$$

Thus this society is implicitly willing to pay $20 million for each avoided death from air pollution.

While this example is based on a contingent valuation study, the most common approach for estimating a VSL is **wage-risk analysis**. In this approach, statistical analysis is used to determine the wage premium that needs to be paid to attract workers to

> **wage-risk analysis** a method used to estimate the value of a statistical life based on the required compensation needed to entice people to high-risk jobs.

particularly risky jobs, while controlling for other factors. Assuming that workers are aware of the risks and have a degree of freedom in choosing jobs, wage-risk analysis can determine the extra wage necessary to induce workers to undertake riskier jobs, such as being loggers, airline pilots, and commercial fishermen.

Recent meta-analyses indicate that VSL estimates can vary considerably.[10] A 2009 study reported estimates ranging from $0.5 to $50 million per avoided death.[11] Across the 32 studies included in this meta-analysis, the mean VSL was $8.4 million but the standard deviation was $7.9 million. A 2015 meta-analysis included additional VSL estimates, for a total of 59 values, and found a slightly higher average VSL of around $11 million.[12]

Both of these meta-analyses relied primarily on VSL estimates from developed nations. VSL estimates in developing countries are typically much lower. For example, a 2014 study in rural China used contingent valuation to estimate a VSL of about $50,000 to $100,000.[13] Other developing country studies have resulted in even lower VSLs, such as a 2006 study in Bangladesh that estimated a VSL of only about $5,000.[14]

A 2012 meta-analysis that included VSL estimates obtained using contingent valuation from both developed and developing countries concluded that a country's GDP per capita had a positive impact on VSL values. The study estimated that the income elasticity of VSL estimates is approximately equal to one, implying that VSL estimates increase in proportion to income.[15]

On one hand, these findings align with our expectations. As we mentioned in Chapter 6, willingness to pay for some beneficial outcome is to some extent a function of ability to pay. The additional compensation necessary to entice workers to undertake risky jobs would be expected to be less in a developing country, where wages are lower. At the same time, these findings present troubling implications for international policy analyses. Consider an early cost-benefit analysis of climate change that valued lost lives in developing countries at only one-fifteenth the value of lost lives in developed countries.[16] This seems to imply that lives in developing countries are somehow "worth" less than lives in developed countries.

Some economists (and many noneconomists) are critical of VSL estimates, based on methodological grounds or ethical objections. The two main methodologies used to derive VSL estimates—contingent valuation and wage-risk analysis—both raise validity concerns. We discussed some of the potential problems with contingent valuation in the previous chapter. Critics of wage-risk studies point out that those who undertake relatively risky jobs are not representative of the broader population. In particular, the wage premium that would be required to attract the average person to a risky job is likely to be higher than the observed wage premium. This could be because the people who undertake risky jobs are likely inherently more accepting of risks and may actually seek risky jobs. It could also be that people in risky jobs have fewer options and are not really undertaking the risk voluntarily in return for higher compensation.

Another methodological issue is that the majority of risky jobs are undertaken by men. About half the wage-risk studies include data only on male job choices. If men and women evaluate risks differently, then extrapolating results from male job choices to the broader population would not be valid.

Another potential problem is using a single VSL for different policy applications. For example, people may not evaluate the risk of cancer from an environmental contaminant in the same way as the risk of a nuclear accident. A 2013 contingent valuation study found that respondents' implied VSL was about $1 million higher when the risk involved death from cancer.[17] The U.S. Environmental Protection Agency is considering a "cancer differential" that would use a higher VSL in CBAs that estimate the benefits of reduced exposure to carcinogens. The VSLs used by government agencies

Box 7.2
THE POLITICS OF VALUING LIFE

The valuation of human lives is not merely an economic issue but a political issue as well, as demonstrated by changes in the VSLs used by U.S. federal agencies in recent years. During the George W. Bush administration, the VSL used by the U.S. Environmental Protection Agency was as low as $6.8 million. But in 2010, the EPA increased their VSL to $9.1 million in a cost-benefit analysis of air pollution standards. The EPA further increased their VSL to $9.7 million in 2013. Under the Obama administration, the Food and Drug Administration also increased its VSL from $5 million in 2008 to $7.9 million in 2010, and to $9.3 million in 2015. Based on higher VSLs, the Transportation Department decided to require stronger car roofs—a regulation that was rejected under the Bush administration as too expensive.

Yet while most federal agencies were increasing their VSLs to around $9 million, the Nuclear Regulatory Commission continued to use a value of only $3 million. Critics pointed out that this relatively low value hindered safety improvements at nuclear power plants that would protect workers and nearby residents. W. Kip Viscusi, a leading economist studying VSLs stated that "The $3 million amount used by the NRC is an outrageously low figure that is way out of line with other government agency practices and the economics literature." Finally, in August 2015 the NRC recommended increasing its VSL to $9 million in future analyses.

Manufacturers and power companies have traditionally advocated the use of cost-benefit analysis for environmental policies, essentially forcing regulators to prove the economic efficiency of environmental improvements. But the recent VSL increases have led them to reconsider their approach. For example, the U.S. Chamber of Commerce (a group representing businesses) has lobbied for Congress to have greater oversight of federal regulators. On the other hand, even environmental groups which remain critical of the VSL methodology praised the Obama administration for increasing the values.

Sources: Appelbaum, 2011; Negin, 2015; McGinty, 2016.

in the United States have generally increased over time, from around $2 million in the 1980s to around $10 million more recently, though the exact values vary by agency. For more on the economic, and political, debate about the VSL in the United States, see Box 7.2.

Other critics reject the entire premise that we should place a numerical value on human lives. They suggest that human life is inherently priceless, and therefore it makes no sense to value risks to human life. Further, some consider the process of reducing human lives to economic analysis fundamentally objectionable on ethical grounds. They suggest that methods other than CBA should be used to make decisions about policies that affect human mortality levels, a topic we'll consider at the end of this chapter.

7.4 OTHER ISSUES IN COST-BENEFIT ANALYSIS

Risk and Uncertainty

In many CBAs, the future outcome of a specific project or proposal is not known with certainty. For example, the operation of a nuclear power plant involves some risk of a serious accident and major release of radiation. Any CBA of a nuclear power plant would

risk term used to describe a situation in which all potential outcomes and their probabilities are known or can be accurately estimated.

have to take this issue into account. How can we incorporate this possibility into a CBA framework?

First, we must realize that risk and uncertainty mean different things to economists.[18] In CBA, **risk** is defined as variability or randomness that can be quantified. For example, statistical studies can define the risks associated with smoking. While no one can tell whether a particular smoker will suffer an early onset of a serious disease or live to a ripe old age, it is clear that smoking increases the chances of early disease and death, and for a large population these risks can be calculated fairly precisely. In situations of risk, the full range of possible outcomes can be listed in a CBA, and likely probabilities can be attached to each outcome. Of course, we do not know which particular outcome will occur, but we believe that we know the probabilities with a reasonable degree of confidence.

For example, in the case of a CBA of a nuclear power plant proposal, we may estimate that the risk of a catastrophic accident is, say, one in 1,000 over the lifespan of the plant.[19] Or in a proposal to develop an offshore oil well, we might estimate the risk of a major oil spill as one in 5,000.[20]

uncertainty term used to describe a situation in which some of the outcomes of an action are unknown or cannot be assigned probabilities.

Uncertainty, in contrast, is defined as variability or randomness that cannot be accurately quantified. The issue of global climate change, discussed in depth in Chapters 12 and 13, demonstrates this. The full effects of global climate change resulting from emissions of greenhouse gases are not accurately predictable. While scientists have generally agreed on a range of possible temperature increases from 1–6°C (about 2–10°F) likely to result over the next century, the global weather system is so complex that dramatic and unpredictable events are possible.

For example, it is possible that positive feedback effects, such as the release of methane from melting of the Arctic tundra, could add huge additional volumes of greenhouse gases to the atmosphere, greatly accelerating warming. Climate change could also lead to changes in ocean currents such as the Gulf Stream, changing the climate of Northern Europe to something like that of Alaska. Despite recent advances in climate change modeling, no one can accurately determine the likelihood of these events.

expected value (EV) the weighted average of potential values.

Risk can be quantitatively incorporated into a CBA, while uncertainty cannot. For a single possible outcome x_i, the **expected value** of that outcome is equal to its probability $P(x_i)$ multiplied by its net benefit (or cost). Thus:

$$EV(x_i) = P(x_i) * NB(x_i).$$

In a situation of risk, we would list all possible outcomes, their probabilities, and their associated net benefits. The expected value of these various possible outcomes is then calculated as:

$$EV(X) = \Sigma_i \, [P(x_i) * NB(x_i)],$$

where $P(x_i)$ is the probability that outcome i will occur, and $NB(x_i)$ is the net benefit of outcome i.

Let's consider an example of a proposal to build a dam for flood control for a cost of $7 million. The expected benefits of the dam will depend on the future risks of a flood, which is a function of precipitation. Suppose that four precipitation scenarios are defined: low, average, high, and extremely high precipitation. In all precipitation scenarios except the extremely high scenario, the dam prevents flooding and thus provides society with benefits.

With extremely high precipitation, the dam bursts and society actually ends up suffering significant damages.

Table 7.3 illustrates these hypothetical outcomes, along with the probability and net benefits of each outcome. The benefits of flood control increase with greater precipitation. The likelihood of a dam failure is only 1 percent, but the damages are very high. When we calculate the expected value across all four scenarios, we obtain a value of \$9.85 million. Assuming that the net benefit estimates reflect all costs and benefits, we would recommend building the dam based on this analysis, assuming no other proposed dam project yields greater net benefits.

risk aversion the tendency to prefer certainty instead of risky outcomes, particularly in cases when significant negative consequences may result from an action.

The formula for expected value does not take into account **risk aversion**—the common tendency to avoid risky situations, particularly those that involve large losses. For example, suppose that you were offered the chance to receive \$100 with certainty versus a 50/50 chance of either winning \$300 or losing \$100. The expected value (EV) of the latter scenario is:

$$\begin{aligned} EV &= [(+\$300 * 0.5) + (-\$100 * 0.5)] \\ &= [+\$150 - \$50] \\ &= \$100. \end{aligned}$$

So in expected value terms, the two scenarios are equal. But many people would prefer to take the \$100 with certainty because of risk aversion.

Going back to our dam example above, we see that the possibility of a dam failure does not have a significant impact on the expected net benefits of the dam. Even though the damages from a dam failure are very high, the low probability of this scenario means that it does not sway the final result very much. If we are risk averse, we may wish to give greater consideration to the possibility of a dam failure. In a quantitative analysis, we could give added weight to any significant negative outcomes. Or we may apply the **precautionary principle**. People living below the dam may not be willing to take the chance, even if remote, of such a huge catastrophe. A similar logic applies to the unpredictable possibilities of extreme global warming effects. In the case of the risk analysis for the dam, climate change could lead to a greater likelihood of extreme precipitation than the 1 percent estimate in Table 7.3. We cannot tell whether such extreme events will occur, but the unknown risk of major planetary disruptions makes us properly nervous and lends urgency to efforts to reduce greenhouse gas emissions.

precautionary principle the view that policies should account for uncertainty by taking steps to avoid low-probability but catastrophic events.

The precautionary principle is especially appropriate when impacts are irreversible. Some types of pollution and environmental damage can be remedied by reducing emissions

Table 7.3 Hypothetical Example of Risk Analysis

Scenario	Net Benefit	Probability	Expected Value
Low precipitation	+ \$5 million	0.27	+ 1,350,000
Average precipitation	+ \$10 million	0.49	+ 4,900,000
High precipitation	+ \$20 million	0.23	+ 4,600,000
Extremely high precipitation	– \$100 million	0.01	– 1,000,000
Total expected value			+ 9,850,000

safe minimum standard the principle that environmental policies on issues involving uncertainty should be set to avoid possible catastrophic consequences.

or allowing time for natural systems to regenerate. Others, like species loss, are irreversible. In cases in which we can adjust for mistakes or change our policies to adapt to new circumstances, an economic balancing of costs and benefits may be appropriate. But when essential natural systems could suffer irreversible damage, it is better to apply a **safe minimum standard** of environmental protection. Damage to the atmospheric ozone layer, for example, could threaten all life on earth by removing an essential barrier to destructive radiation. As a result, international treaties have sought to impose a complete ban on many ozone-depleting substances, regardless of any economic benefits that they might offer.

In dealing with issues involving risk and uncertainty, good judgment is required regarding which risks can reasonably be estimated and given an expected monetary value. Just because outcomes are not known with certainty does not mean that economic analysis of environmental impacts is inappropriate. But caution is needed to recognize cases in which economic valuation of possible outcomes fails to capture the full impact on human health or ecosystems.[21]

Benefit Transfer

Conducting a CBA can be time consuming and expensive. Often federal and state agencies require quantification of environmental costs and benefits but lack the resources to fund original analyses. In such cases, the agency may locate similar studies and rely upon them to obtain estimates. The practice of using existing studies to obtain an estimate for a new situation is known as **benefit transfer**.

benefit transfer assigning or estimating the value of a resource based on prior analysis of one or more similar resources.

Consider an example of benefit transfer. In 2001 the U.S. EPA was conducting a CBA of different standards for arsenic in drinking water. One of the human health impacts of arsenic consumption is bladder cancer, which does not tend to be fatal. Rather than conduct an original study of the willingness to pay to avoid a case of nonfatal bladder cancer, the EPA applied benefit transfer. However, no studies were available on the valuation of damages from bladder cancer or any other nonfatal cancer. According to the EPA study, the most-similar estimate was a study that used contingent valuation to estimate people's willingness to pay to avoid a case of chronic bronchitis.[22] Obviously, bladder cancer and chronic bronchitis are two rather different diseases. Thus one may question the validity of such a transfer.

Other applications of benefit transfer appear more reasonable. For example, in 1996 an oil spill off the coast of Rhode Island caused a reduction in recreational marine fishing. As part of the legal claim for damages, the government agencies involved in the case needed an estimate of the consumer surplus of a day of marine fishing in the area of the spill. Again, an original analysis was not conducted, and the agencies sought to transfer a benefit estimate. After reviewing more than 100 studies, the agencies ended up transferring an estimate based on a travel cost study of marine recreational fishing off the coast of New York.[23]

Numerous studies have tested the validity of benefit transfer. By conducting an original analysis to obtain a "correct" benefit value, such as the value of an ecosystem service, and then comparing the value to transferred values from other studies, a researcher can test the accuracy of the transferred values. A 2013 meta-analysis considered 31 studies that tested the validity of benefit transfers, and found that significant errors are possible if one relies upon transferred values. The analysis found that the errors introduced with transferred values ranged from zero to over 7,000 percent![24] The average error was 172 percent but this average was significantly influenced by a few large errors. The median error was significantly lower at 39 percent. In one study of recreation benefits, errors averaged 80–88 percent with a range of 12–411 percent.[25]

The potential errors of benefit transfer can be reduced by adhering to several guidelines developed by environmental economists.[26] Historically, most benefit transfers have involved policy makers relying upon a single study that most closely reflects their given application, such as the marine fishing example discussed above. However, one should always consider the quality of the original study. Also, older studies, even if they are high-quality, may no longer be relevant due to changes in preferences, incomes, or demographics. Rather than relying upon a single study, it is preferable to collect evidence from multiple studies to explore how benefit values vary in different situations. Economists have recommended developing online databases of environmental and natural resource benefit values to ensure that policy makers have all relevant studies available to them. Finally, government agencies that rely upon benefit transfer should develop clear guidelines for conducting those transfers, and potentially subject their analyses to peer review.

Even when benefit transfers adhere to these recommendations, we have no assurance that the transferred values are accurate. As benefit transfer becomes increasingly common, should economists continue to use this practice if the validity is questionable? Of course, primary studies are preferable to benefit transfer if the resources are available. But benefit transfer does provide an estimate when information would not be available otherwise. Benefit transfer may be more suitable for some situations, such as preliminary screening of policy options, and less suitable for other applications, such as determining damages in a legal case. Ultimately:

> decision makers will have to use their own judgment to make a tradeoff between using benefit transfer values and conducting a primary study to generate original WTP estimates. [I]n principle, an analyst might be able to correct for some of the errors in the [transferred] values to be used in real world benefit transfer. It is important to acknowledge, however, that benefit transfer is not a panacea . . . but an approach to effectively utilize existing information and resources to provide a rough estimate when a "first best" valuation study is not affordable.[27]

7.5 COST-BENEFIT ANALYSIS EXAMPLE

A relatively simple example of a CBA can illustrate some of the practical issues that often arise. Suppose that a government agency is evaluating a proposal to build a dam. We start by listing some of the costs and benefits associated with the dam, as summarized in Table 7.4. The list is not meant to be comprehensive—these are only the impacts we consider in this example. You may well think of other costs and benefits that should be included.

Table 7.4 Potential Costs and Benefits Associated with Dam Construction Proposal

Potential Costs	Potential Benefits
1. Construction costs	1. Flood control
2. Operations and maintenance costs	2. Recreation
3. Environmental damages	3. Hydropower supply
4. Risk of dam failure	

Let's assume that the construction costs of the dam are \$150 million, to be paid \$50 million per year over a three-year construction period. Normally, construction costs would be paid over a longer time period, funded by a loan, but in this case we assume three annual payments. During the construction period, the dam generates no benefits. The discount rate is set at 5 percent. We can use our present value equation to determine the present value of the construction costs over the three-year construction period as (all impacts will be expressed in millions of dollars):

$$\begin{aligned} PV &= 50 + (50/1.05) + (50/1.05^2) \\ &= 50 + 47.62 + 45.35 \\ &= 142.97. \end{aligned}$$

Note that this calculation assumes that we do not discount in the first (current) year. Suppose that we collect information on the other categories of costs and benefits as:

- Annual operations and maintenance costs are \$8 million.
- Annual recreation benefits are \$15 million. Note that the reservoir obviously is not available for study until after the dam is constructed. Thus we need to rely on some kind of benefit transfer in order to provide an estimate of the recreation benefits before the site is built.
- Annual hydropower benefits are \$5 million. This estimate would be based on the consumer surplus of those using the electricity and the producer surplus (profits) of the electricity provider.
- Environmental damages from the dam are \$10 million annually. These damages likely include lost habitats and reduced fish population, as dams can prevent the spawning of certain species.
- Annual flood control benefits depend upon the distribution of expected precipitation patterns. In normal years, assume that there is no risk of flooding and thus no benefits. Assume that normal years occur 70 percent of the time (probability of 0.7). In a wet year, assume that the damage prevented by the dam is \$20 million in crop damage, property damage, and other avoided impacts. Suppose that wet years occur every five years (a probability of 0.2). Further, assume that a very wet year occurs every 10 years, and in these years the damage prevented is \$50 million.

We thus have a situation of risk (as opposed to uncertainty) in which we know the probability of all possible outcomes and their economic impacts. The expected value of annual flood control benefits using the formula from earlier in the chapter is:

$$\begin{aligned} EV &= (0.7 * 0) + (0.2 * 20) + (0.1 * 50) \\ &= 0 + 4 + 5 \\ &= 9. \end{aligned}$$

Finally, let's assume that the dam is in an area prone to earthquakes, and there is a chance that a major earthquake will cause the dam to fail and produce catastrophic damages. Let's suppose that an engineering estimate indicates that the risk of dam failure from an earthquake is only 0.01 percent per year or a probability of 0.0001. However, if the dam does fail, damages would be \$5 billion in terms of material damage and human lives lost. Note that a VSL would be used to value the potential human deaths. The annual expected damage from a dam failure would be:

$$
\begin{aligned}
EV &= \$5{,}000 * 0.0001 \\
&= 0.5.
\end{aligned}
$$

This annual value is much lower than any of the other impacts. Thus it will not have a significant impact on our final results. However, we may want to adjust this calculation if we are risk averse or if there is any reason to doubt the engineering estimates, creating a situation of uncertainty rather than known risk.

The other piece of information that we need is the expected lifespan of the dam. We assume that the dam will last for 50 years, after which no costs or benefits will occur. Again, this is perhaps unrealistic, and we do not consider any permanent ecological damage, but this allows us to keep the example relatively simple.

We are now able to bring all our impacts together to produce a net benefit estimate. For the purposes of discounting, in the first year of the dam's operation the value of *n* in our discounting formula will be 3. This is because it takes three years to construct the dam. A spreadsheet can be used to calculate the present value of each category of impacts for each year. (For instructions on how to use Microsoft Excel to calculate present values, see Appendix 7.1.)

Table 7.5 presents the detailed calculations for the first few and last few years of the analysis (the results for Years 6–48 have been omitted), as well as the total present value for each impact. Note that the analysis extends to Year 52 to account for the three years of construction (Years 0–2) and the 50-year dam lifespan (Years 3–52).

Consider the environmental costs, which start to occur in Year 3. The environmental costs in Year 3 are \$10 million, which convert to a present value of:

$$
\begin{aligned}
PV &= \$10 \text{ million} / (1.05)^3 \\
&= \$8.64 \text{ million}.
\end{aligned}
$$

By the time we get to the end of the dam's lifetime, the effect of discounting becomes much more significant. Impacts are reduced by more than a factor of 10 in the last few years.

Table 7.5 Annual Present Value of Costs and Benefits of Dam Construction Proposal (in Millions), Selected Years

	Costs				Benefits		
Year	Construction	Operations	Environmental	Dam Failure	Recreation	Hydropower	Flood Control
0	50.00	0.00	0.00	0.00	0.00	0.00	0.00
1	47.62	0.00	0.00	0.00	0.00	0.00	0.00
2	45.35	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	6.91	8.64	0.43	12.96	4.32	7.77
4	0.00	6.58	8.23	0.41	12.34	4.11	7.40
5	0.00	6.27	7.84	0.39	11.75	3.92	7.05
...	...	...	...	...	...	...	...
49	0.00	0.73	0.92	0.05	1.37	0.46	0.82
50	0.00	0.70	0.87	0.04	1.31	0.44	0.78
51	0.00	0.66	0.83	0.04	1.25	0.42	0.75
52	0.00	0.63	0.79	0.04	1.19	0.40	0.71
Total Present Value	142.97	132.47	165.59	8.28	248.38	82.79	149.03

Over the dam's lifetime, the present value of all costs is:

$$PV_{costs} = 142.97 + 132.47 + 165.59 + 8.28$$
$$= 449.31.$$

The present value of all benefits is:

$$PV_{benefits} = 248.38 + 82.79 + 149.03$$
$$= 480.20.$$

Thus the **net present value (NPV)** is:

$$NPV = PV_{benefits} - PV_{costs} = 480.20 - 449.31 = 30.89.$$

net present value (NPV) present value of benefits minus present value of costs.

sensitivity analysis an analytical tool that studies how the outputs of a model change as the assumptions of the model change.

So should we build the dam based on these results? Benefits exceed costs by about \$30 million, so that would suggest building the dam is economically efficient. But as mentioned earlier, we do not know whether building the dam will necessarily produce the most social benefits for a given cost. Perhaps investing the \$150 million construction cost in building schools or reducing air pollution would yield greater net benefits. We should also consider whether the scale of the dam project is optimal. Perhaps a smaller, or larger, dam would produce greater net benefits, or a higher benefit-cost ratio.

A good CBA should include **sensitivity analysis**. This considers whether the recommendation changes when we change some of the assumptions of the analysis. Perhaps the most common type of sensitivity analysis is to change the discount rate. In our example, the construction costs are paid first, whereas net benefits occur in the future (i.e., for each year starting in Year 3 in Table 7.5, the benefits exceed the costs). So increasing the discount rate tends to reduce net benefits and make the project seem less appealing. In fact, if we change the discount rate to 8 percent instead of 5 percent, the proposal has a negative net present value of about \$30 million, and we would not recommend building the dam.

Another type of sensitivity analysis might consider the effect of risk aversion to the possibility of a dam failure. Even with a 5 percent discount rate, an adjustment for risk aversion (such as increasing the present value of this impact by a factor of five) could result in net costs, and a recommendation not to build the dam.

Sensitivity analysis is important because it tells us whether our results are robust to changes in the underlying assumptions. If different sensitivity analyses do not result in changes to our policy recommendation, we can feel relatively confident in proceeding with that recommendation. However, if our recommendation differs with reasonable changes in the assumptions, we may be unable to make a firm recommendation. Finally, we also need to determine whether we have excluded any costs and benefits or left some impacts unquantified. This may be another reason why a CBA could be inconclusive.

7.6 CONCLUSION: THE ROLE OF COST-BENEFIT ANALYSIS IN ENVIRONMENTAL POLICY DECISIONS

Cost-benefit analyses of environmental policies are particularly difficult and controversial because several of the most important benefits of environmental improvements are difficult to quantify. First, nonuse values can only be estimated using contingent valuation. We saw in the last chapter that the validity of this method is a subject of debate among economists. Second, the benefits of reduced mortality rates are estimated using the VSL methodology—another controversial valuation approach. Third, environmental policies often involve up-front costs and longer-term benefits. This makes the choice of a discount rate critically important. A lower discount rate tends to support greater environmental protection.

While CBA can provide definite policy recommendations in some instances, often the results will produce ambiguous results because of excluded factors or sensitivity analysis. In such cases different approaches may be needed. One alternative is to rely on a different process for setting policy objectives and having economics play a more limited role. With **cost-effectiveness analysis**, economic analysis merely determines the least-cost way of achieving a policy goal.

cost-effectiveness analysis economic analysis that seeks to determines the least-cost way of achieving a given policy goal.

Suppose, for example, that we have established a goal of cutting sulfur dioxide pollution, a major cause of acid rain, by 50 percent.[28] This might be done by requiring highly polluting coal power plants to install scrubbers; by imposing taxes or fines based on emission levels; or by issuing tradable permits for a certain level of emissions, with the total number of permits not exceeding 50 percent of current levels (these policies are discussed in greater detail in Chapter 8). Assuming economic analysis can provide reliable estimates of the costs arising from each of these policies, cost-effectiveness analysis can tell us which option is the most economically efficient way to achieve our policy goal.

Clearly it makes sense to adopt the least-cost method of reaching a given goal. In this approach, we do not rely on economic analysis to tell us *how much* we ought to reduce pollution—that decision is made based on other factors, including scientific evidence, political discussion, and ordinary common sense. But economic analysis is used to tell us how to choose the most efficient policies to achieve a desired result.

Another alternative to CBA, involving consideration of broader social and political factors, is called **positional analysis**. In this approach, estimates of the economic costs of a particular policy are combined with an evaluation of the effects on different groups of people, possible alternative policies, social priorities, individual rights, and goals and objectives other than economic gain. There is no single "bottom line," and it is recognized that particular outcomes may favor some groups over others.[29]

positional analysis a policy analysis tool that combines economic valuation with other considerations, such as equity, individual rights, and social priorities; it does not aim to reduce all impacts to monetary terms.

For example, the construction of a major dam may require relocation of large numbers of people. Even if the dam's economics appear favorable, these people's right to remain in their homes may be given a greater social priority. Such judgments cannot be made on a purely economic basis. However, some of the valuation techniques we have discussed may be useful in defining economic aspects of what must ultimately be a social and political decision.[30]

Up to this point, we have seen that traditional environmental economics has several core theories and methods that can provide environmental policy guidance. The theories discussed in Chapters 3–5 generally point out how policy interventions can produce more economically efficient, and environmentally beneficial, outcomes. To use economic analysis to provide specific policy recommendations, we must rely upon the valuation approaches discussed in Chapter 6, and sometimes on the cost-benefit analysis techniques discussed in this chapter. We have seen that this is a challenging task, raising numerous issues of validity, assumptions, and ethics.

In the next chapter, we will look at more specific analysis of pollution control policies, which will complete our coverage of standard environmental economics analysis and techniques. Then we will turn to some of the issues that define the core of what is known as ecological economics in Chapter 9, and the topic of national income and environmental accounting in Chapter 10.

Summary

Cost-benefit analysis can be used to evaluate proposed projects and government actions. Environmental factors are often involved in cost-benefit analysis and can be some of the most controversial to value. One important issue is the valuation of future costs and benefits. Economists use the technique of discounting to balance the needs of the present and future. Selection of an appropriate discount rate is important and can significantly affect the results of cost-benefit studies. The socially appropriate discount rate may be different from the commercial discount rate used to evaluate financial investment returns.

Another important and controversial issue is the valuation of human lives. While we must somehow evaluate tradeoffs between environmental protection expenditures and mortality risks, the VSL methodology seeks to estimate society's willingness to pay to avoid a death due to environmental contaminants in terms of economic value.

Cost-benefit analysis also requires the assessment of risk. When risks are known with a reasonable degree of certainty, it is possible to estimate the expected value of various outcomes using known probabilities, and to include this expected value in cost-benefit analysis. When outcomes are uncertain, and probabilities are not known or not easy to estimate, alternative approaches may be needed to take into account risk aversion and the need for precaution.

Using these techniques for discounting, valuation, and risk assessment, it is possible to construct a complete cost-benefit analysis for a particular project or proposal. The results can be used to guide policy decisions, but it is important to keep in mind the possible sensitivity of results to assumptions made, and the limitations of valuation techniques in capturing all relevant environmental and social factors.

Key Terms and Concepts

benefit transfer

benefit/cost ratio

cost-benefit analysis

cost-effectiveness analysis

discount rate

discounting

expected value (EV)

net benefits

net present value (NPV)

positional analysis

precautionary principle

present value

pure rate of time preference

real or inflation-adjusted dollars

risk

risk aversion

safe minimum standard

sensitivity analysis

social discount rate/social rate of time preference (SRTP)

uncertainty

value of a statistical life (VSL)

wage-risk analysis

Discussion Questions

1. Suppose that you are asked to conduct a cost-benefit study of a proposed coal-fired power plant. The plant will be built on the outskirts of a residential area and will emit a certain volume of pollutants. It will require a substantial amount of water for its cooling system. Industries in the region argue that the additional power is urgently needed, but local residents oppose construction. How would you evaluate social and environmental costs and weigh them against economic benefits?

2. As mentioned in the text, under U.S. law federal agencies must use cost-benefit analysis to evaluate major policy proposals. Do you agree with this requirement, in particular for environmental policies? How much weight do you believe should be given to the results of cost-benefit analyses when making policy decisions? Discuss how economic, health, and environmental criteria should be balanced in formulating regulations.

3. Suppose that the government of a developing country is considering the establishment of a national park in a scenic forested area. Local opposition arises from those who wish to use the forest land for timbering and agriculture. But the national park would draw both local and foreign visitors as tourists. Could cost-benefit analysis aid the decision on whether to establish the park? What factors would you consider, and how would you measure their economic value?

Exercise

The World Bank is considering an application from the country of Equatoria for a large dam project. Some costs and benefits of the project (dollar values) are as follows:

- Construction costs: $500 million per year for three years
- Operating costs: $50 million per year
- Hydropower to be generated: 3 billion kilowatt hours per year
- Price of electricity: $0.05 per kilowatt hour
- Irrigation water available from dam: 5 billion gallons per year
- Price of irrigation water: $0.02 per gallon
- Agricultural product lost from flooded lands: $45 million per year
- Forest products lost from flooded lands: $20 million per year

There are also additional, less easily quantifiable, losses: human costs to villagers who will be forced to move, watershed damage, and ecological costs of habitat destruction. It is also possible that the new lake area may contribute to the spread of water-borne diseases.

a) Do a formal cost-benefit analysis encompassing all of the quantifiable factors listed above. Assume that the lifespan of the dam is 30 years. As in the example in Table 7.5, assume that construction begins now (in Year 0). All other impacts start once the dam is completed (in Year 3) and continue for 30 years (until Year 32). Refer to Appendix 7.1 to make the necessary calculations using Excel. Use two possible discount rates: 10 percent and 5 percent. For each rate, what is the present value of the dam's benefits and costs? What are your policy recommendations for each discount rate? Remember that there are also unquantified impacts.

b) Now consider an alternative project: a number of smaller dams constructed so as not to flood significant agricultural or forest lands. For this project, total construction costs are exactly half the costs of the big dam project (but still over a three-year period), operating costs are unchanged, and power/irrigation benefits are also half as much. But there is no damage to farmland or forest, and there are no ecological or resettlement costs. Conduct a cost-benefit analysis of this project, again using a 5 percent and a 10 percent discount rate. What is the present value of this scenario's costs and benefits at each discount rate?

c) Considering all your results, what are your policy recommendations? Do you prefer building the one large dam or the several smaller dams? Finally, which discount rate, 5 percent or 10 percent, do you think is most appropriate for your cost-benefit analysis? Why?

Notes

1. The term "benefit-cost analysis" (BCA) is also used. The two are synonymous.
2. Dollar values are adjusted for inflation by the use of a price index that represents the general price level compared to a base year (a well-known example is the Consumer Price Index [CPI]). For example, if the price index is 120, compared to 100 in the baseline year, a current dollar value of $240 would be equivalent to an inflation-adjusted value of $240/(120/100) = $200.
3. Numerous examples of this tendency exist, such as people running up large credit card bills or failing to save adequately for retirement.
4. The rate varies depending upon the length to maturity (three to 30 years). See U.S. OMB, 2016.
5. Stern, 2007.
6. Evans, 2005.
7. Nordhaus, 2014.
8. Weitzman, 2001.
9. Layton and Levine, 2003, p. 543.
10. A meta-analysis, as noted in the previous chapter, reviews existing research to identify common findings and trends.
11. Bellavance *et al.*, 2009.
12. Viscusi, 2015.
13. Wang and He, 2014.
14. Mahmud, 2006.
15. Biausque, 2012.
16. See Ackerman and Heinzerling, 2004.
17. Alberini and Ščasný, 2013.
18. For a discussion of the difference, see Staehr, 2006.
19. About 400 nuclear plants have operated worldwide in the past five decades, with two catastrophic accidents, in Chernobyl, Ukraine, and Fukushima, Japan. This implies an accident likelihood of one in several hundred, so 1 in 1,000 would be a conservative estimate.
20. This rough estimate might be based on the actual experience of one major oil spill in the Gulf of Mexico, out of several thousand wells drilled.
21. For discussion of the limitations of economic valuation, see, for example, O'Brien, 2000; Toman, 1994.

22. U.S. EPA, 2001.
23. NOAA *et al.*, 1999.
24. Kaul *et al.*, 2013.
25. Shrestha and Loomis, 2003.
26. Richardson *et al.*, 2015.
27. Shrestha and Loomis, 2003, p. 95.
28. This was, in fact, the goal set by the U.S. Environmental Protection Agency under the Clean Air Act Amendments of 1990.
29. For an exposition of the basis of positional analysis, see Söderbaum, 1999.
30. For a discussion of the interaction between estimation techniques and underlying values, see Gouldner and Kennedy, 1997.

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APPENDIX 7.1: USING EXCEL TO PERFORM PRESENT VALUE CALCULATIONS

Present value calculations for analyses that cover many years can be performed easily using Microsoft Excel. Let's assume that we want to calculate the present value of a $20,000 annual benefit that occurs over a 20-year period starting in Year 3 (relative to now, which is Year 0). The discount rate is 3 percent.

We would first set up a column in our spreadsheet for the years, shown as Column A in Table A7.1. The benefit will occur for 20 years starting in Year 3, so the numbers go up to 22. Note that the benefits for Years 0–2 are zero. We entered the annual benefit of $20,000 in Cell E2 and the discount rate in Cell E5. Entering these off to the side will allow us to change these values easily if we want to consider a different scenario, such as a different discount rate.

For Year 3 the present value of the benefit is:

$$\begin{aligned} PV &= \$20{,}000/(1 + 0.03)^3 \\ &= \$18{,}303. \end{aligned}$$

To perform this calculation in Excel, we would enter the following exactly into Cell B5:

=E2/((1+E5)^A5).

The = is necessary to indicate you are entering a formula. Entering E2 tells Excel to use the value in Cell E2 (20,000) as the numerator of the equation. The denominator refers to the cells with the discount rate and the year. When you enter this formula, you should get a value of 18,303. (We round off all numbers to the nearest whole number in this appendix.)

Next, copy the formula from Cell B5 to Cell B6, to obtain the present value for Year 4. You should get a value of 0—obviously not correct. If you look at the copied formula (click on Cell B6), you will see that every cell reference has been shifted down by one line. The copied formula should read:

=E3/((1+E6)^A6).

While we wanted to refer to Cell A6 instead of Cell A5 (Year 4 instead of Year 3), we wanted to maintain the references to Cells E2 and E5. To do this in Excel, when we enter a formula we place "$" before the column and the row to fix a reference to a specific cell. Then whenever the formula is copied, the reference won't change.

Go back to the formula in Cell B5 and revise it as follows:

=$E$2/((1+$E$5)^A5).

Now the references to Cells E2 and E5 are fixed, and only the reference to Cell A5 will adjust when the formula is copied. The value in Cell B5 should still be 18,303. If we copy this revised formula to Cell B6, the new value should be 17,770. The formula is Cell B6 should be:

=$E$2/((1+$E$5)^A6).

Table A7.1 Using Excel to Perform Present Value Calculations

	A	B	C	D	E
1	Year	Benefit			
2	0	0		Benefit =	20,000
3	1	0			
4	2	0		Discount	
5	3	18,303		Rate =	0.03
6	4	17,770			
7	5	17,252			
8	6	16,750			
9	7	16,262			
10	8	15,788			
11	9	15,328			
12	10	14,882			
13	11	14,448			
14	12	14,028			
15	13	13,619			
16	14	13,222			
17	15	12,837			
18	16	12,463			
19	17	12,100			
20	18	11,748			
21	19	11,406			
22	20	11,074			
23	21	10,751			
24	22	10,438			
26					
27		280,469	TOTAL PV		

So we are now discounting by four years instead of three. We can then copy this formula down to all the remaining years. With each additional line down, we are discounting by an additional year. The value for the last year should be 10,438. Summing over all the years (Excel has a simple summation command), we get a total present value of $280,469, as shown in Cell B27.

With the input variables on the side, we can easily revise our analysis. Suppose that we want to redo our calculations with a 5 percent discount rate. All we would need to do is change the value in Cell E5 from 0.03 to 0.05. All calculations will automatically update. The new total present value should be $226,072 instead of $280,469.

CHAPTER 8

Pollution: Analysis and Policy

Chapter 8 Focus Questions

- What are the best policies for controlling pollution?
- How can we balance the costs and benefits of pollution regulation?
- Should industries be allowed to purchase permits to pollute?
- How can we deal with long-lived and cumulative pollutants?

8.1 THE ECONOMICS OF POLLUTION CONTROL

One of the ecological services provided by natural systems is a **sink function**—the capacity to absorb waste and pollution. Although essential to human life and economic systems, this function has often been abused by excessive pollution. This raises two questions for environmental policy. First, how much pollution is acceptable—given that any society must emit some waste products? Second, how can we best control or reduce pollution to this acceptable level?

sink function the ability of natural environments to absorb wastes and pollution.

How Much Pollution Is Too Much?

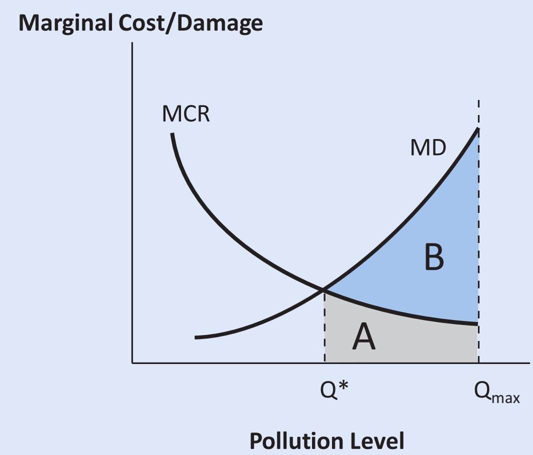
You may think the answer to this question is that any pollution is too much. As noted in Chapter 3, environmental economists think in terms of the concept of an **optimal level of pollution**. While some might believe that the optimal level of pollution is zero, economists would argue that the only way to achieve zero pollution is to have zero production. If we want to produce virtually any manufactured good, some pollution will result. We as a society must decide what level of pollution we are willing to accept. Of course, we can strive to reduce this level over time, especially through better pollution control technologies, but as long as we wish to produce goods we will have to determine the "optimal" level of pollution.

optimal level of pollution the pollution level that maximizes net social benefits.

We've already discussed pollution as a negative externality in Chapter 3. According to the logic of external costs and benefits, an unregulated market outcome for a good that generates pollution results in "too much" production. The "optimal" level of production occurs when the externality is fully internalized, resulting in a lower level of production and a lower level of pollution. We can now broaden this analysis by considering the overall emissions of a particular pollutant, recognizing that the pollutant is emitted through the production of a wide range of goods and services. If the pollutant is unregulated, then firms essentially have no incentive to take steps to reduce their emissions. We refer to this unregulated level of pollution as Q_{max} as shown in Figure 8.1. Firms can reduce pollution below Q_{max}, but it will involve costs such as installing pollution control equipment or substituting low-polluting materials. If firms must reduce pollution below Q_{max}, then a rational, profit-maximizing approach implies that firms will institute the lowest-cost pollution-reduction options first, then proceed to more expensive actions.[1] As pollution levels are reduced closer to zero, the cost of additional pollution reduction will rise. Thus we see in Figure 8.1 that the marginal cost of pollution reduction (curve MCR) rises as we move from Q_{max} to lower levels of pollution (i.e., moving from right to left).

Next, consider the marginal damage associated with pollution. We will take air pollution as an example. Considering the concept of total economic value discussed in Chapter 6, this damage includes effects on human health, reduced air visibility, and harm to ecosystems. The first few units of pollution cause relatively little damage because ecosystems can process and break down a certain amount of pollution, and the levels are generally too low to have significant health impacts. Eventually, levels become high enough to start causing damage such as asthma, noticeable reductions in visibility, and ecological degradation. A small amount of automobile exhaust on a clear day may be a minor annoyance, but the same amount added to a smoggy area at rush hour could trigger significant breathing and health problems. Thus the marginal damage of pollution starts off small and grows as the level of pollution rises.

Figure 8.1 The Optimal Level of Pollution



This is represented by curve MD in Figure 8.1. Note that this curve can also be viewed as the marginal benefits of pollution reduction, or the avoided damage. Starting at Q_{max} and moving from right to left on the graph, there are very great benefits from the first units of pollution reduced (since the damages caused by these units were very high), and the marginal benefit declines as cleanup proceeds.

equimarginal principle the balancing of marginal costs and marginal benefits to obtain an efficient outcome.

At Q_{max} the marginal damage of pollution is high, while the costs to reduce pollution are relatively low. Social welfare would increase if pollution were reduced below $Q_{max.}$ This is true for every unit of pollution above $Q*$, which is the optimal level of pollution. At this point the marginal benefits of pollution reduction just equal the marginal costs. This balancing of marginal costs and marginal benefits is known as the **equimarginal principle**.[2]

The total cost to firms of reducing pollution from Q_{max} to $Q*$ is area A—the area under their marginal cost curve. The total social benefits of reducing pollution to $Q*$ are represented by areas (A + B). Thus the net increase in social welfare from reducing pollution is area B.

It is easy enough to find $Q*$ on our graph, but how can we identify it in real life? This is not so easy, because we are unlikely to know the shape and location of these curves with any precision. As we saw in Chapter 6, valuation of environmental damage is an imprecise science and involves many judgment calls. Control costs may be easier to estimate based on industry estimates, but they also are often uncertain.

Industries often estimate control costs that turn out to be too high once control policies actually go into effect. For example, the automobile industry has often argued that proposals to reduce tailpipe emissions would boost vehicle costs by a large margin. In practice, the implementation of significantly tighter vehicle emission standards has had little impact on costs.

Similarly, the electrical power industry predicted high costs for sulfur oxide (SO_x) reduction, but the real costs (as shown by the price of SO_x emissions permits, discussed below) were considerably lower. On the other hand, control costs can sometimes run higher than estimated, as has often proved the case for cleaning up toxic waste facilities.

Despite these uncertainties, the equimarginal principle is central to the economic analysis of pollution control policies. Even if we cannot define the precise goal, we know that it will be better to use efficient policies—those that give the greatest result for the lowest cost—rather than inefficient policies that bring relatively higher costs and reduced benefits. Economic analysis can help us to formulate efficient policies and analyze the advantages and disadvantages of different approaches. In the following sections, we consider possible options for pollution control policies from this point of view.

Picking a Pollution Control Policy

There are four basic approaches to pollution control:

1. Pigovian (or pollution) taxes: as discussed in Chapter 3, Pigovian taxes amount to a charge levied per unit of pollution emitted.
2. Transferable (tradable) pollution permits: these allow firms to emit only the level of pollution for which they have permits. Tradability implies that firms can buy and sell these permits, with low-emitting firms able to sell extra permits and high-emitting firms able to purchase additional permits.
3. Pollution (or emissions) standards: standards require all firms to pollute below maximum allowable levels or reduce pollution to a certain percentage below a baseline level. These standards can also specify a given level of efficiency for products such as appliances and motor vehicles.
4. Technology-based regulations: these include requirements that all firms use a certain type of technology or install specific equipment.

Pigovian (pollution) tax a per-unit tax set equal to the external damage caused by an activity, such as a tax per ton of pollution emitted equal to the external damage of a ton of pollution.

transferable (tradable) pollution permits permits that allow a firm to emit a certain quantity of pollution.

pollution (or emissions) standards a regulation that mandates firms or industries to meet a specific pollution level or pollution reduction.

technology-based regulation pollution regulation by requiring firms to implement specific equipment or actions.

There is no universal answer regarding which pollution control approach is the best. Different approaches may be preferable in different circumstances. In the real world, normally a combination of approaches is used.

In this chapter, we approach questions about the level and method of pollution control primarily in terms of economic analysis. At the same time, we bear in mind the limitations of a purely economic perspective. In dealing with the impacts of pollution, we may not be able to measure all the relevant costs and benefits in economic terms. This is especially true when multiple pollutants affect the environment, when cumulative ecosystem damage and degradation are at issue, or when subtle effects of persistent pollutants are poorly understood.

In such cases, economic analysis may not capture the full scope of ecosystem effects. Economic analysis, however, is essential for understanding how pollution control policies affect firms and individuals and the role that economic incentives play in altering behavior with regard to the production and consumption of pollution-generating products. We now consider each of the four pollution control approaches in more detail.

8.2 POLICIES FOR POLLUTION CONTROL

Emissions Standards

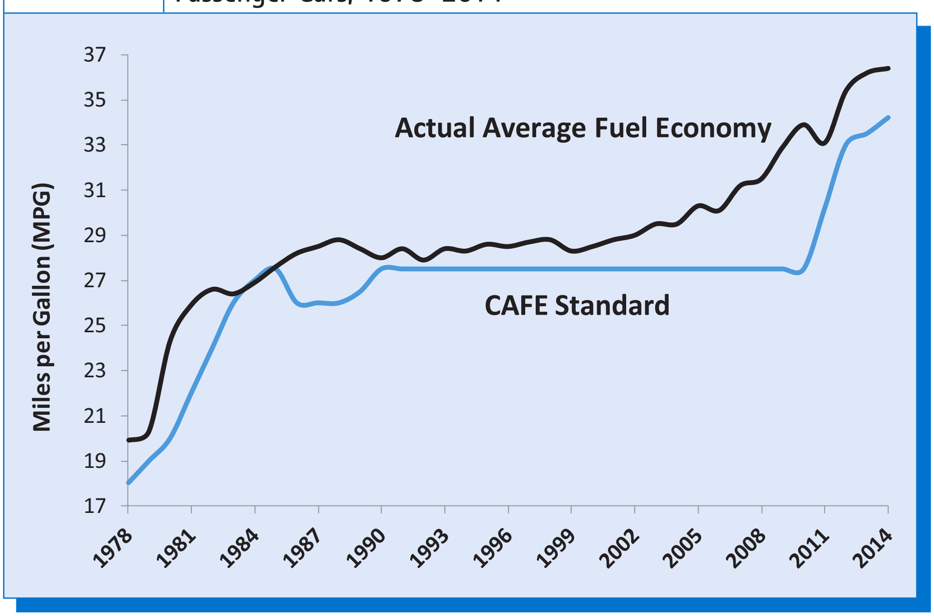
Setting standards for emissions or other pollution sources is a common approach to reducing pollution. Government departments such as the U.S. Environmental Protection Agency can set standards for particular industries or products, subject to legislative guidelines. Many people experience the use of standards at an annual automobile inspection. Cars must meet certain standards for tailpipe emissions; a car that fails must have the problem corrected before it can receive an inspection sticker.

What are the advantages and disadvantages of standards from an economic perspective? The clear advantage is that standards can specify a definite desired result. This is particularly important in the case of substances that pose a clear hazard to public health. By imposing a uniform rule on all producers, we can be sure that no factory or product will produce hazardous levels of pollutants. In extreme cases, a regulation can simply ban a particular pollutant, as has been the case with DDT (a toxic pesticide) in most countries.

Systems that require all economic actors to meet the same standard, however, may have the problem of inflexibility.[3] Fixed standards work well when pollution-generating firms or products are relatively similar. For example, different models of automobiles are sufficiently alike to impose the same emissions rules on all. Light-duty trucks in the United States, including sport utility vehicles, must therefore meet the same emissions standards as passenger cars. But consider an industry with many plants of different sizes and ages. Will it make sense to have the same rule for every plant? A particular standard might be too difficult for the older plants to meet, forcing owners to shut them down. But the same standard might be too lax for more modern plants, allowing them to emit pollution that could have been eliminated at low cost.

Requiring all firms or products to meet the same standards is normally not cost effective. It is cheaper for firms that can reduce pollution at a low marginal cost to reduce pollution more than firms that have a high marginal reduction cost. Thus requiring all firms to reduce pollution by the same amount, or meet the same standards, is not the cheapest way to achieve a given level of pollution reduction. Another problem with standards is that after firms meet

Figure 8.2 CAFE Standards and Actual Average Fuel Economy for New Passenger Cars, 1978–2014



Source: U.S. Department of Transportation, 2014.

Note: CAFE = Corporate Average Fuel Economy.

them they have little incentive to reduce pollution further. An illustration of this problem is the motor vehicle fuel economy program in the United States, known as CAFE (Corporate Average Fuel Economy). After automakers met the fuel economy standards, and consumers did not demand further fuel efficiency gains, automakers stopped trying to make further efficiency gains, as shown in Figure 8.2.

In the late 1970s and early 1980s, the average fuel efficiency of new passenger cars increased from about 20 to 28 miles per gallon (mpg) in order to meet a CAFE standard of 27.5 mpg. But the standard stayed the same for about 20 years, and during most of that period, the average fuel economy of new cars also stayed about the same. Only when gas prices rose in the later 2000s did average fuel efficiency increase in response to consumer demand and the awareness that CAFE standards were set to start increasing in 2011. For more on the recent increase in CAFE standards, see Box 8.1.

Box 8.1

U.S. SETS HIGHER FUEL EFFICIENCY STANDARDS

In August 2012 the Obama Administration announced new rules that will require automakers to nearly double the fuel efficiency of new vehicles by 2025. The combined corporate average fuel economy (CAFE) standard for cars and light trucks is scheduled to rise from 29.7 miles per gallon (mpg) in 2012 to 54.5 mpg in 2025.

"These fuel standards represent the single most important step we've ever taken to reduce our dependence on foreign oil," said President Obama. "This historic agreement builds on the progress we've already made to save families money at the pump and cut our oil consumption. By the middle of the next decade our cars will get nearly 55 miles per gallon, almost double what they get today. It'll strengthen our nation's energy security, it's good for middle class families and it will help create an economy built to last."

"Simply put, this groundbreaking program will result in vehicles that use less gas, travel farther, and provide more efficiency for consumers than ever before—all while protecting the air we breathe and giving automakers the regulatory certainty to build the cars of the future here in America," said Transportation Secretary Ray LaHood. "Today, automakers are seeing their more fuel-efficient vehicles climb in sales, while families already saving money under the Administration's first fuel economy efforts will save even more in the future, making this announcement a victory for everyone."

The new rules were endorsed by 13 major automakers and generally considered a victory for environmentalists. While the new rules could increase the price of new vehicles by $2,000 to $3,000, these costs will be more than offset by projected fuel savings of about $8,000 per vehicle by 2025. In addition to the new standards, new incentives will encourage the spread of fuel-efficient technologies, including incentives for electric, plug-in hybrid, and natural gas vehicles.

The administration also said the new rules would cut vehicle greenhouse gas emissions in half by 2025, eliminating 6 billion tons of emissions over the course of the program. The program could generate hundreds of thousands of jobs by increasing the demand for new technologies.

However, as of the time this book went to press (mid-2017), the Trump administration had indicated they would re-examine the stricter standards, claiming they will reduce economic growth. A lengthy rulemaking process will be required to actually reduce the standards, and weaker standards will surely be challenged in the courts.

Sources: NHTSA, 2012; Vlasic, 2012.

Technology-Based Approaches

A second approach to environmental regulation is to set requirements that firms or products incorporate a certain pollution-control technology. For example, in 1975 the United States required that all new automobiles include a catalytic converter to reduce tailpipe emissions. While auto manufacturers are free to design their own catalytic converters, each must meet certain emissions specifications.

best available control technology a pollution regulation approach in which the government mandates that all firms use a control technology deemed most effective.

A similar concept is that firms adopt the **best available control technology (BACT)**.[4] An example of this is the Clean Water Act in the United States, which requires that effluents be controlled using "the best practicable control technology currently available."[5] Similar technology-based regulations have been enacted to control air pollution in the United States and the European Union. Technology-based approaches generally do take costs into consideration. For example, in the UK water pollution regulations require the adoption of the best technology "not entailing excessive costs."

The mandated BACT can change over time as technologies improve. However, BACT regulations may create little incentive for innovation. If a firm invents a new technology for pollution control that increases costs, it may withhold the technology from regulators in order to avoid a requirement that it be adopted.

Perhaps the main advantage of technology-based regulation is that enforcement and monitoring costs are relatively low. Unlike a pollution standard, which requires that firms' pollution levels be frequently monitored to ensure compliance, a BACT regulation might require only occasional checks to ensure that the equipment is installed and functioning properly.

Technology-based approaches are unlikely to be cost-effective because they do not provide firms with the flexibility to pursue a wide range of options. Like compliance in meeting pollution standards, BACT implementation costs will vary among firms. Thus it is unlikely that a given level of pollution reduction will be achieved at the lowest cost. Technology-based approaches may, however, offer a cost advantage due to standardization. If all firms must adopt a specific technology, then widespread production of that technology may drive down its production cost over time.

Pollution Taxes

Pollution taxes, along with tradable pollution permits, are considered **market-based approaches** to pollution regulation because they send information to polluters about the costs of pollution without mandating that firms take specific actions. Individual firms are not required to reduce pollution under a market-based approach, but the regulation creates a strong incentive for action.

As we saw in Chapter 3, a pollution tax on emissions reflects the principle of internalizing external costs. If producers must bear the costs associated with pollution by paying a per-unit charge, they will find it in their interests to reduce pollution so long as the marginal control costs are less than the tax.

market-based pollution control pollution regulations based on market forces without specific control of firm-level decisions, such as taxes, subsidies, and permit systems.

Figure 8.3 illustrates how an individual firm will respond in the presence of a pollution tax. Once again, Q_{max} is the level of pollution emitted without any regulation. If a uniform charge, or pollution tax, equal to T_1 is imposed, pollution will fall to Q_1. Producers will find it preferable to reduce pollution to this level, at a total cost of E, equal to the area under the marginal cost of reduction (MCR) curve between Q_1 and $Q_{max.}$ Otherwise, if the firm maintained pollution at Q_{max} it would have to pay a fee of (E + F) on these units of pollution. Thus the firm saves area F by reducing pollution.

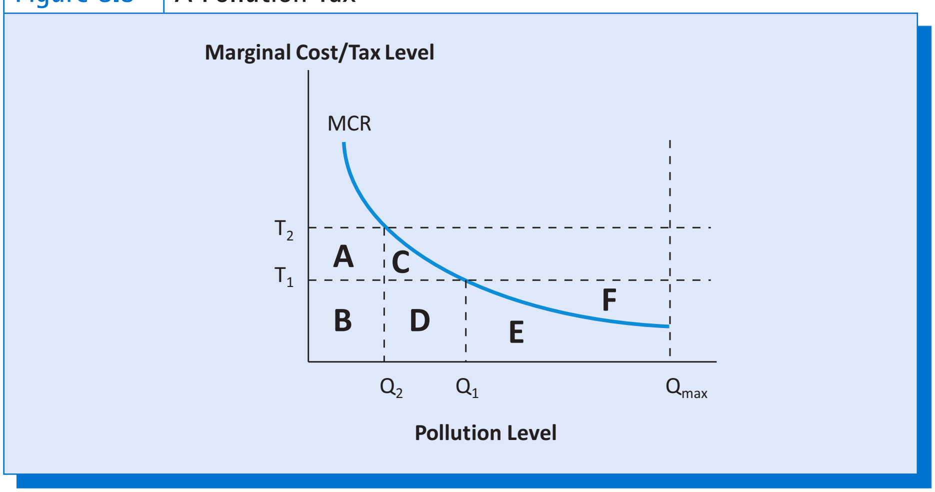
After reducing pollution to Q_1, the firm will still need to pay the tax on its remaining units of pollution, equal to areas (B + D). The total cost to the firm from the pollution tax is the sum of its reduction costs and tax payments, or areas (B + D + E). This is less than areas (B + D + E + F), which is what they would have to pay in taxes if they undertook no pollution reduction. The firm's response to the tax is cost-effective, as any other level of pollution different from Q_1 would impose higher costs.

If the per-unit charge is set higher, at T_2, producers will reduce pollution further, to Q_2. This will involve control costs of (C + D + E), and pollution taxes of (A + B). The extra units of pollution reduction involve higher marginal costs, but so long as these costs are less than T_2, producers will find it worthwhile to undertake the extra expense and thus avoid paying the fee on the units of pollution between Q_1 and Q_2.

This cost-minimizing logic ensures that cleanup expenses are directed to wherever they can achieve least-cost pollution reduction. Here we have a different application of the equimarginal principle—marginal control costs are being equalized among all producers.[6] If the tax level reflects the true damage costs, it will also be true that marginal control costs for all producers are equal to marginal benefits from damage reduction.

We can note that the same goal of efficient pollution reduction may be achieved by the use of a subsidy for pollution reduction rather than a tax on pollution emitted. If producers are paid per unit of pollution reduced, they will make a similar judgment about the level of pollution reduction that is most profitable. For example, if a subsidy equal to T_1 is offered for each unit of pollution reduction, producers will find it worthwhile to cut pollution to Q_1, paying area E in control costs but collecting (E + F) in subsidy for a net profit of F. This has the same policy effect as a tax of T_1, but a different distributional implication. Rather than collecting revenues (B + D), the government pays the firm (E + F), leaving the producers better off by (B + D + E + F). Politically, this approach may be more acceptable to industry, but it may also make pollution control unacceptably costly in terms of government budgets.

Figure 8.3 A Pollution Tax



We can use a simple mathematical example to further demonstrate how a firm will respond in the presence of a pollution tax. Suppose a firm has a marginal cost of pollution reduction of:

$$MCR = 30 + 2Q$$

where Q is the quantity of pollution reduced, in tons, relative to Q_{max} (the amount of pollution emitted in the absence of regulation). Thus without any regulation, Q would be zero. Let's assume that Q_{max} is 100 tons. We can draw the firm's MCR curve in Figure 8.4. Note that in this case we have reversed the *x*-axis—we are measuring *pollution reduction* rather than the level of pollution. So the maximum potential pollution reduction is 100 tons, going left to right.

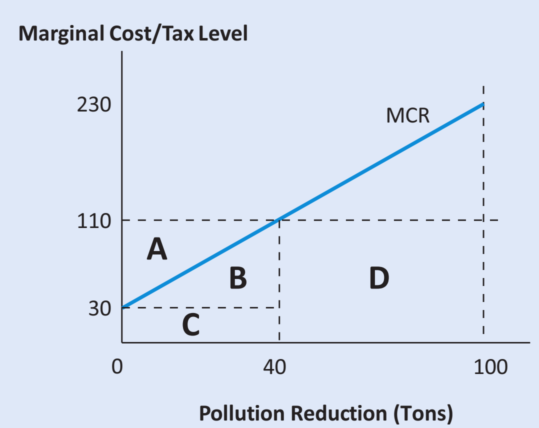
Suppose that a pollution tax of \$110 per ton is enacted. If the firm did not reduce its pollution at all, it would have to pay \$110 per ton for all 100 tons of pollution, or \$11,000. This is shown as areas (A + B + C + D) in Figure 8.4. But instead the firm should act in a cost-effective manner, reducing pollution as long as its reduction costs are less than the tax. We can solve for the optimum quantity of pollution reduction by setting the MCR equal to the tax amount:

$$110 = 30 + 2Q$$
$$80 = 2Q$$
$$Q = 40$$

Thus the firm will reduce pollution by 40 tons, leaving 60 tons of remaining pollution. The firm will still have to pay the \$110 tax on 60 tons of pollution, or \$6,600. This is represented by area D in Figure 8.4. The firm's total pollution reduction cost is the area under its MCR curve for each ton reduced, or areas (B + C). Note that area B is a triangle with a base of 40 and a height of 80 (110 − 30), and area C is a rectangle with a base of 40 and a height of 30. So we can calculate the firm's pollution reduction costs as:

$$\begin{aligned} \text{Reduction costs} &= (40 * 80 * 0.5) + (30 * 40) \\ &= \$1{,}600 + \$1{,}200 \\ &= \$2{,}800. \end{aligned}$$

Figure 8.4 Pollution Tax Example



Considering both its reduction costs and the tax, the total cost to the firm is \$9,400, which is cheaper than paying \$11,000 in taxes if it didn't reduce pollution at all. Any other level of pollution reduction other than 40 tons will entail higher overall costs to the firm.

Note that firms with different MCR curves will reduce pollution by different amounts. Those with higher MCR curves will reduce pollution less, while those with lower costs will reduce pollution more. The effect of each firm operating in a cost-minimizing manner is that a given level of total pollution reduction will be achieved at the lowest overall cost. Unlike standards and technology-based approaches, pollution taxes are thus economically efficient.

Tradable Pollution Permits

Economic efficiency in pollution control is clearly an advantage. One disadvantage of pollution taxes, however, is that it is very difficult to predict the total amount of pollution reduction that a given tax will produce. It depends on the shape of each firms' MCR curve, which as we have noted is usually not known to policy makers.

Suppose that the policy goal is a more precise and definite reduction in pollution levels, either throughout a country or within a certain region. For example, in 1990 the U.S. Environmental Protection Agency set a goal of 50 percent reduction in sulfur and nitrogen oxide (SO_x and NO_x) emissions that cause acid rain. What is the best way to achieve such a specific target, while also achieving economic efficiency?

One approach, used in the U.S. Clean Air Act Amendments of 1990, is to set up a system of tradable pollution permits. The total number of permits issued equals the desired target level of pollution. These permits can then be allocated freely to existing firms or sold at auction. Once allocated, they are fully tradable, or transferable, among firms or other interested parties. Firms can choose for themselves whether to reduce pollution or to purchase permits for the pollution they emit—but the total volume of pollution emitted by all firms cannot exceed the maximum amount set by the total number of permits.[7]

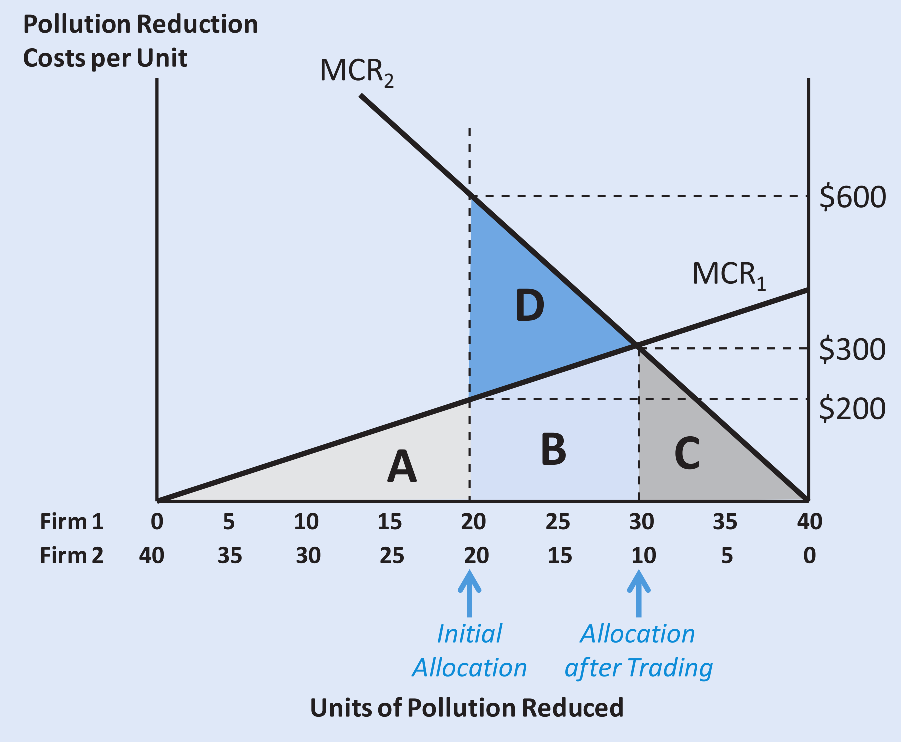
In this system it is also possible for private groups interested in reducing pollution to purchase permits and permanently retire them, thus reducing total emissions below the original target level. The permits may expire after a given time period, after which fewer new permits could be issued, resulting in lower overall pollution levels. Figure 8.5 illustrates a simplified version of a tradable permit system.

In this simplified example, we have assumed that there are only two firms, each emitting 50 units of pollution before any regulation, for total emissions of 100 units. The policy goal is a total reduction of 40 units of pollution. The sum of the reductions by the two firms must therefore equal 40. Figure 8.5 shows the different ways in which a total reduction of 40 units can be distributed between the two firms, as measured along the *x*-axis. Note that every point on the *x*-axis represents a total reduction of 40 units, but split in different ways among the two firms.

The marginal reduction costs for the two firms differ. The MCR curves for the two firms are plotted in different directions on the same axis, with pollution reduction by Firm 1 going from left to right and by Firm 2 from right to left. This is merely a graphical trick to make it easy to identify the point at which the equimarginal principle is satisfied (i.e., the point at which the marginal control costs for the two firms are equal).

Before the permit trading system is put in place, the two firms together are emitting 100 units of pollution. To achieve the reduction goal of 40 units, a total of 60 pollution permits must be issued. Suppose that the initial allocation of permits is 30 to each firm. If permits cannot be traded, each firm must cut back its emission from 50 to 30—a reduction of 20. This is shown in the middle of the graph (the "Initial Allocation"). At this point, the marginal control cost is \$200 for Firm 1 and \$600 for Firm 2. This is the same result that would occur if a uniform regulation limited each firm to a maximum of 30 emissions units.

Figure 8.5 A Tradable Pollution Permit System



This result achieves the policy goal in terms of emissions reductions, but it is economically inefficient. Each firm's total control cost can be seen on the graph as the area under their MCR curve.[8] Since the MCR curves are linear, each firm's total reduction costs equal the area of a triangle. Firm 1's total cost for pollution reduction is shown as area A, which equals:

$$\textit{Firm 1 reduction costs} = 20 * 200 * 0.5$$
$$= \$2{,}000.$$

Total reduction costs for Firm 2 are represented by areas (B + C + D), or:

$$\textit{Firm 2 reduction costs} = 20 * 600 * 0.5$$
$$= \$6{,}000.$$

The combined cost to achieve 40 units of pollution reduction is (A + B + C + D), or $8,000.

Now let's suppose that the firms are allowed to trade permits. Firm 2 is incurring relatively high marginal costs to reduce pollution by 20 units. At the margin, it must spend $600 to achieve the last unit of reduction. Thus it would be willing to spend up to $600 to purchase an additional permit so that it does not have to reduce pollution so much. Would Firm 1 be willing to sell a permit to Firm 2? If Firm 1 sells one pollution permit, it would then have to reduce its pollution by an additional unit to avoid exceeding its allowance. We see that at the margin it would cost Firm 1 about $200 to reduce its pollution by one more unit (from 20 units of reduction to 21 units). So Firm 1 would require at least $200 in compensation to sell a permit.

Because Firm 1 needs a minimum of $200 to sell a permit, and Firm 2 is willing to pay up to $600, we have considerable space in which to negotiate an agreement. Note that this is essentially the same situation that we had in Chapter 3 with the Coase Theorem.

Firm 1 will continue to offer permits for sale to Firm 2 as long as it can receive a price greater than its reduction costs. Firm 2 will continue to purchase permits as long as it can buy them for less than their reduction costs. Trading will continue until the MCR curves are equal, with Firm 1 selling 10 permits to Firm 2 (the "Allocation After Trading"). Note that beyond this point (i.e., moving further to the right), Firm 1 would ask a price higher than $300 while Firm 2 would be willing to pay less than $300, thus no further trades can be negotiated. The price for the last permit sold will be $300, which represents the marginal reduction costs for both firms at the point where Firm 1 is reducing pollution by 30 units and Firm 2 by 10 units. For simplicity, assume that all permits sell for the equilibrium price of $300 each.

We can now compare the total costs to each firm before and after trading, as shown in Table 8.1. At the new equilibrium, total reduction costs for Firm 1 are represented by the triangle (A + B), which is equal to:

$$\begin{aligned} \textit{Firm 1 reduction costs} &= 30 * 300 * 0.5 \\ &= \$4{,}500. \end{aligned}$$

However, Firm 1 also receives $300 per permit for 10 permits, for an income of $3,000. Thus Firm 1's net costs are only $1,500, as shown in Table 8.1. Compared to their pre-trading costs of $2,000, Firm 1 is now better off by $500.

Firm 2's reduction costs at the new equilibrium are represented by triangle C, which is equal to:

$$\begin{aligned} \textit{Firm 2 reduction costs} &= 10 * 300 * 0.5 \\ &= \$1{,}500. \end{aligned}$$

But Firm 2 must also purchase 10 permits, for an additional cost of $3,000. Thus Firm 2's total costs are $4,500. Firm 2 is also better off than before trading, when its costs were $6,000.

As the permit trades are simply a transfer of income across the two firms, not an additional total cost, the total reduction costs after trading are now $6,000. The same pollution reduction goal has now been achieved at a lower cost as a result of trading. Area D (equal to $2,000) represents the net savings from this more efficient solution.

Table 8.1 Cost Efficiency of a Tradable Permit System

	Before trading			
	Units Reduced		Reduction Costs	
Firm 1	20		$2,000	
Firm 2	20		$6,000	
Total	40		$8,000	
	After trading			
	Units Reduced	Reduction Costs Permit	Income or Cost	Net Costs
Firm 1	30	$4,500	+ $3,000	$1,500
Firm 2	10	$1,500	– $3,000	$4,500
Total	40	$6,000	0	$6,000

In a sense, a tradable permit system combines the advantages of direct regulation and an emissions tax. It allows policy makers to set a definite limit on total pollution levels, while using the market process to seek an efficient (i.e., cost minimizing) method of achieving the goal. It is economically advantageous for the firms involved, as our example shows, achieving a given amount of pollution reduction for the minimum economic cost. In addition, other interested parties can strengthen pollution control by purchasing and retiring permits, and pollution controls can be tightened over time by reducing the overall number of permits issued.

The trading equilibrium shown in Figure 8.5 is consistent with the equimarginal principle, because at the trading equilibrium the marginal reduction costs for all firms are equal. For simplicity, our example used only two firms, but the principle can easily apply to an industry with many firms. Firms will benefit by purchasing permits whenever the permit price is below their marginal reduction costs or selling permits whenever the permit price exceeds these costs.

Box 8.2
SULFUR DIOXIDE EMISSIONS TRADING

The 1990 Clean Air Act Amendments created a national program to allow trading and banking of sulfur dioxide (SO_2) emissions, the primary cause of acid rain. The program applies to more than 2,000 large electricity plants, which must hold permits in order to emit SO_2. Most permits are freely allocated to plants based on their capacity to generate electricity. About 3 percent of the permits are auctioned off every year. Permits may then be traded, normally with brokers facilitating trades. While most trades occur between two electricity-generating plants, some permits are purchased by environmental groups or individuals (and even environmental economics classes!) and then "retired" to reduce the overall quantity of SO_2 emissions.

Economic theory suggests that a system of tradable permits can reduce pollution at a lower overall cost than a uniform standard. Dallas Burtraw, an economist with Resources for the Future, notes that the "SO_2 allowance market presents the first real test of economists' advice, and therefore merits careful evaluation" (2000, p. 2). After over 20 years in operation, how has the program performed?

To evaluate the policy, the effects of emissions trading must be isolated from other factors. Declining prices for low-sulfur coal in the 1990s and technological advances would have reduced the cost of lowering emissions even without a trading system. Economic simulation models comparing the SO_2 program to an emissions standard suggest that the cost savings from trading were about 50 percent. The savings are even greater when compared to a technology-based approach.

The emissions targets of the SO_2 program have been met at lower cost than originally anticipated. Acidification problems in the northeastern states, widespread in the past, have declined. However, aquatic systems in the southeastern states are expected to continue to decline without further emissions reductions. And while the program has been effective, analysis of the marginal benefits and marginal costs of emissions suggests that further emissions reductions would produce even larger net benefits.

Burtraw concludes that the SO_2 market has "been liquid and active, and according to most observers [has] worked well in achieving the emissions caps at less cost than would have been achieved with traditional approaches to regulation. There is evidence that both process and patentable types of innovation are attributable to the [SO_2 program]. At the same time, there is evidence that some cost savings have not been realized. Moreover, despite substantial emissions reductions, ultimate environmental goals have not been achieved" (Burtraw and Szambelan, 2009, p. 2).

Sources: Burtraw, 2000; Burtraw and Szambelan, 2009.

It does not necessarily follow, however, that a tradable permit system is always the ideal pollution control policy. Tradable permits have been used successfully for sulfur dioxide reduction under the Clean Air Act Amendments of 1990 and have been widely discussed as a tool for reduction of global carbon dioxide emissions (for more on the sulfur dioxide trading program, see Box 8.2). But numerous factors must be considered in deciding whether pollution taxes, permits, technology-based approaches, or direct regulation are the best policy tools for a particular goal. We now consider some of the factors to keep in mind when deciding which pollution policy approach may be most effective in a particular circumstance.

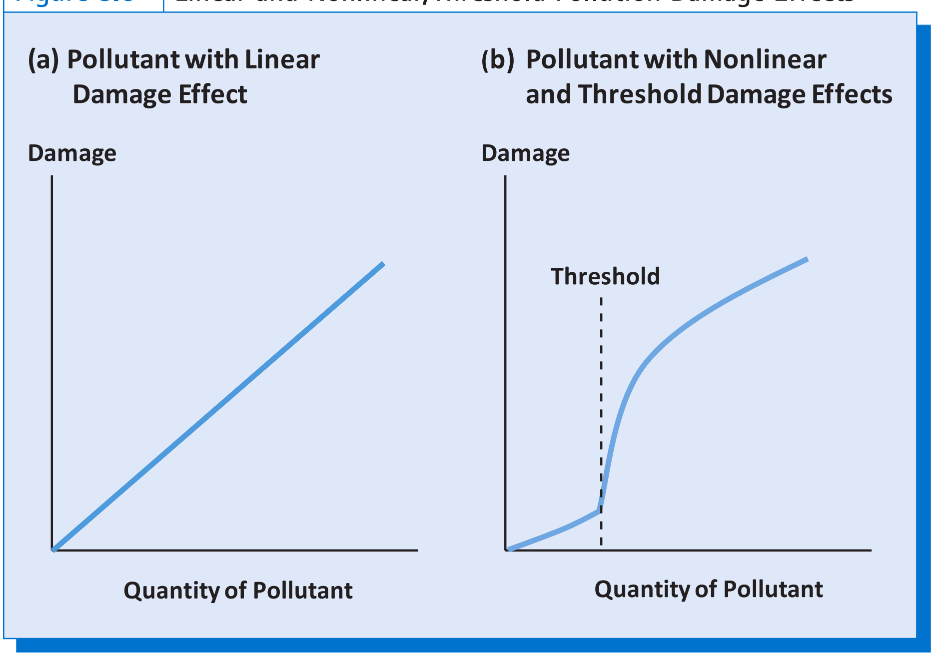
8.3 THE SCALE OF POLLUTION IMPACTS

One of the major questions in formulating effective pollution control policies is the nature of the pollution involved. Are its effects primarily local, regional, or global? Do the effects increase linearly with the amount of pollutant, are there **nonlinear** or **threshold** effects? (See Figure 8.6.)

nonlinear or threshold effects pollution damages that are not linearly correlated with pollution levels.

In Figure 8.6a we observe that environmental damages increase linearly as the quantity of pollution increases. But consider, for example, a heavy metal pollutant such as lead. If a production facility is emitting lead as a pollutant, those living in the vicinity of the plant face a grave health threat. A small amount of lead in the blood can lead to serious neurological and mental damage, especially in children. We can say that the threshold for acceptable levels of lead in the environment is low, and above this threshold damages can increase quite significantly as pollution exceeds this threshold (see Figure 8.6b).

Figure 8.6 Linear and Nonlinear/Threshold Pollution Damage Effects



Another important factor in this case is the distribution of the pollutant's impact. Lead can be a **local pollutant**, meaning that its health and ecosystem impacts occur relatively close to where it is emitted into the environment.[9]

Market mechanisms such as pollution taxes or permits are generally ineffective in preventing damage from lead pollution. Under a permit system, a high-polluting but profitable plant could simply purchase permits and continue polluting, with serious consequences for local residents if concentrations are above the threshold level. Similarly, the managers of such a plant might choose to pay a pollution tax rather than cut back emissions. These market-based systems might achieve regional or national control of overall lead emissions, but they would fail to protect local residents. In a case like this, regulations must specify strong emissions standards for *every* plant in order to protect the public. A technology-based approach could also work for a local pollutant, as long as it keeps pollution concentrations to an acceptable level. For some widely used substances, such as leaded gasoline or lead paint, complete prohibition is the only effective policy.

local and regional air pollutants pollutants that cause adverse impacts only within the area where they are emitted.

Market-based policies work better in the case of regional and global pollutants. Sulfur oxides (SO_x) are **regional pollutants**. These gases, which contribute to acid rain, are emitted by many facilities, especially coal- and oil-fired power plants. They are carried by the wind over wide areas, creating regional pollution. In devising policies to limit these regional damages, it makes little difference which sources reduce pollution output, provided that the desired reduction targets are met over a region. This is therefore a good case for the application of a tax or permit scheme.

As we have noted, the Clean Air Act Amendments of 1990 used tradable permits with successful results. Considerable overall reduction in SO_x emissions has been achieved, and the price of an emissions permit has fallen as emissions reduction technology has improved (see Box 8.2).[10] But tradable permits may not be the best choice in all cases. Even if they can succeed in reducing overall emissions, they may still allow high levels of pollution in certain localities. Here it is important to distinguish between **uniformly mixed** and **nonuniformly mixed** pollutants. A uniformly mixed pollutant is emitted by many different sources and has relatively uniform concentration levels across a region or the world. Greenhouse gases, such as carbon dioxide, are uniformly mixed pollutants. Whether a ton of carbon dioxide is emitted in the United States, China, or Africa is essentially irrelevant, as each will increase the overall concentration of carbon dioxide in the atmosphere by the same amount.

uniformly mixed pollutants any pollutant emitted by many sources in a region resulting in relatively constant concentration levels across the region.

nonuniformly mixed pollutants pollutants that cause different impacts in different areas, depending on where they are emitted.

hotspots locally high levels of pollution, for example, surrounding a high-emitting plant; hotspots can occur under a pollution trading scheme.

Nonuniformly mixed pollutants may be emitted in varying concentrations and remain at different levels in different locations. Examples of nonuniformly mixed pollutants include lead and particulate matter. Nonuniformly mixed pollutants may create **hotspots**, which are local areas with unacceptably high levels of pollution. While a tradable permit system specifies the total level of pollution, one or more firms in a local area may purchase an excessive amount of permits, leading to very high localized pollution. Similarly, firms with high MCR curves may choose to maintain pollution levels at Q_{max} and pay the tax on all emissions. Standards set at a local level or technology-based approaches are generally better at eliminating hotspots.

Another example of a nonuniformly mixed pollutant is ground-level ozone. As was mentioned in Chapter 7 (Box 7.1), in 2015 the EPA reduced the standard for ground-level ozone from 75 ppb (parts per billion) down to 70 ppb. However, individual states have time to comply with the lower standard. By 2021 states are required to submit attainment plans to the EPA, and the new standards eventually go into effect later in the 2020s.

Cumulative and Global Pollutants

Pollution problems are often long lived. Organochloride pesticides such as DDT, polychlorinated biphenyls (PCBs), and chlorofluorocarbons (CFCs) remain in the environment for many decades. As emissions of such pollutants continue, the total amounts in land, air, water, and living things steadily increase. Even if pollution levels are reduced to zero, concentrations can remain at harmful levels for decades.

The analysis that we have discussed regarding marginal costs of pollution damage is appropriate for **flow pollutants**—those that have a short-term impact and then dissipate or are absorbed harmlessly into the environment. For a **cumulative or stock pollutant** that persists in the environment for long time periods, however, we need a different kind of analysis and different control policies.

The issues of cumulative pollution are especially important for **global pollutants**. Carbon dioxide, methane, and chlorofluorocarbons emitted into the atmosphere last for decades and have worldwide effects. As mentioned earlier, it does not matter whether a ton of carbon dioxide is emitted in the United States or China, as its impact will be essentially the same. Pollutants like DDT and other persistent pesticides also spread worldwide and are found in high concentrations in the bodies of people and animals in the Arctic, where these substances have never been used.

cumulative or stock pollutant a pollutant that does not dissipate or degrade significantly over time and can accumulate in the environment, such as carbon dioxide and chlorofluorocarbons.

flow pollutants a pollutant that has a short-term impact and then dissipates or is absorbed harmlessly into the environment.

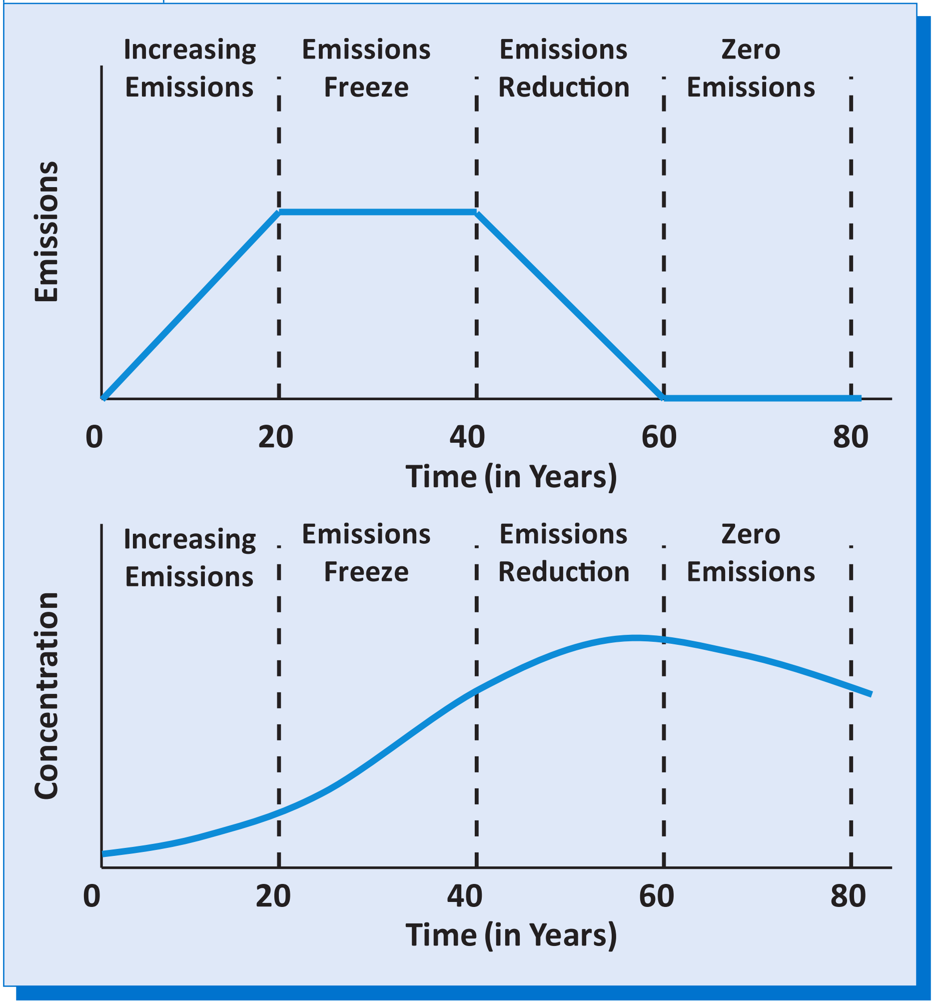
global pollutant pollutants that can cause global impacts such as carbon dioxide and chlorofluorocarbons.

Polychlorinated biphenyls (PCBs), formerly used as insulators in electrical systems, have caused severe river pollution that remains a major problem decades after their use was banned. Methyl mercury absorbed by fish in rivers and oceans can remain for many years, becoming more concentrated as it moves up the food chain. As the importance of such issues increases, we must consider appropriate responses. Often these may be quite different from the policies used to respond to shorter-term air and water pollution.

Consider the case of ozone-depleting substances, which include chlorofluorocarbons (CFCs) as well as other chemicals, such as the pesticide methyl bromide. These gases, used for cooling equipment, such as air conditioners, as well as other industrial applications, eventually migrate to the upper atmosphere, where they attack the earth's protective ozone layer. The damaging effects of CFCs were first identified in the 1970s, but many years passed before the scale of the problem was sufficiently well understood to motivate significant action on a global scale (discussed in Box 2.1).

To analyze the issue of a cumulative pollutant such as CFCs, we must consider both emissions and the accumulated concentration of CFCs in the atmosphere. Figure 8.7 shows the relationship between the two in simplified form. Unlike our previous graphs, this one includes time, shown on the horizontal axis. The top graph shows a simplified emission pattern over four periods of 20 years each. In the first period, emissions increase steadily. In the second, a freeze is imposed on emissions levels, with no further increase permitted—but emissions continue at the level that they had already reached. In the third period, there is a steady reduction of emissions to an eventual zero level.[11] In the fourth period, emissions remain at zero.

Figure 8.7 Emissions and Accumulated Concentration of a Stock Pollutant



Note the relationship between emissions and the concentration. As emissions rise at a steady rate, shown by the straight line in the first part of the upper graph, concentration rises at an increasing rate.[12] The concentration continues to rise steadily even when a freeze is imposed on emissions during the second period. Only when emissions are steadily reduced, eventually to zero, in the third period does the rate of increase in the concentration start to slow, finally reaching a maximum accumulation that occurs, in our example, about forty years after the maximum emission level was first reached. And only in the final period, after emissions have been held steady at zero, do concentrations steadily decline.

This simplified diagram conveys the essence of the problem with a global cumulative pollutant. Since damages are related to accumulated concentrations, not annual emissions, environmental impacts become steadily more severe, continuing for many years after control measures are taken. Dealing with cumulative pollutants requires urgent action and stringent policy measures. Even with such measures, irreversible damage may occur. The environmental accumulations on our graph may take many decades after year 80 before they decline to a safe level.

8.4 ASSESSING POLLUTION CONTROL POLICIES

Policy Making Under Uncertainty

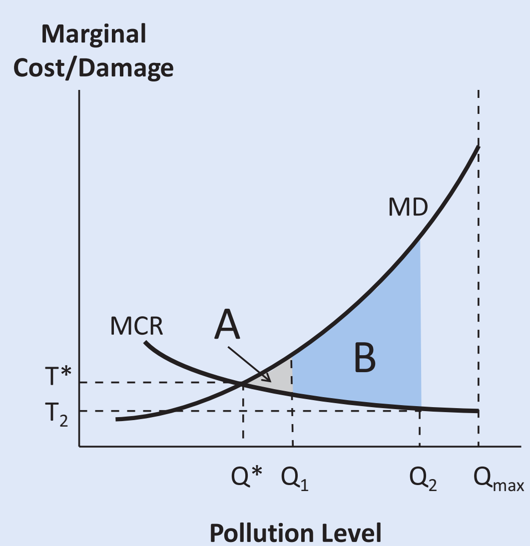
We saw in Figure 8.1 that the "optimal" level of pollution balances the marginal damages from pollution and the marginal costs of pollution reduction. Pollution taxes and tradable permits can achieve the "optimal" level of pollution, but normally we do not have enough information to fully plot out the marginal damage and marginal cost curves. In the case of a tax, we may set the tax at the "wrong" level, leading to a socially inefficient level of pollution, possibly too much but also potentially too little pollution. In the case of a permit system, we may allocate too many or too few permits, also leading to inefficiency.

In the likely case of uncertainty, the choice between a tax or permit system is partially dependent upon the shapes of the marginal cost of reduction (MCR) and marginal damage (MD) curves shown in Figure 8.1. Even if we do not know the exact curves, we may know whether each curve is likely to be relatively steep or relatively flat. We can use this information to help us decide which policy would be preferable.

Suppose that for a particular pollutant the marginal damage curve is relatively steep, meaning that marginal damage rises quickly as the level of pollution increases. At the same time, assume the per-unit costs of pollution reduction for this pollutant tend to be fairly stable, with marginal costs rising only slowly as pollution reduction increases. This is shown in Figure 8.8. Note that as in Figure 8.1 we again show the pollution level on the *x*-axis, rather than the level of pollution reduction.

We know the optimal level of pollution is Q^*. We could achieve this by allocating a number of permits equal to Q^* or by setting a pollution tax equal to T^*. But suppose that we lack the information to determine either of these values accurately. First let's consider the impact

Figure 8.8 Pollution Regulation under Uncertainty with Steep Marginal Damages



of allocating the wrong number of permits. Suppose that we allow too much pollution by setting the number of permits equal to Q_1 instead of Q^*. For every unit of pollution between Q_1 and Q^* the marginal damages exceed the marginal reduction costs, so Q_1 is inefficient relative to the optimal level of pollution. The amount of the inefficiency is equal to area A in the graph. This represents a loss of potential benefits.

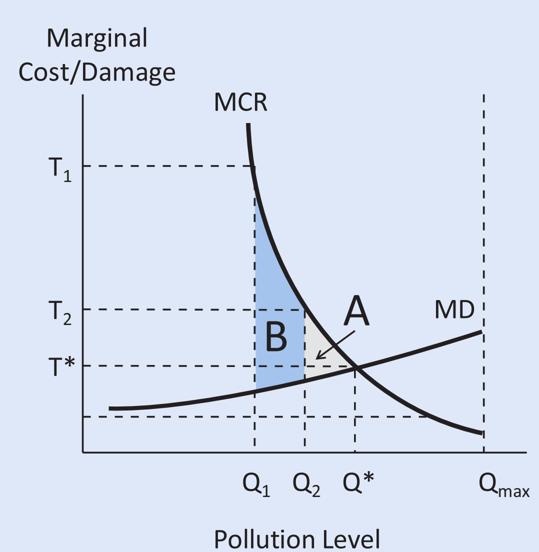
Now suppose instead that we institute a pollution tax but set the tax slightly too low, at T_2 instead of T^*. With a relatively flat MCR curve, a small error in the tax level results in a pollution level of Q_2—significantly more pollution than optimal. Now the unrealized benefits, relative to pollution at Q^*, are areas (A + B). Getting the tax wrong has resulted in a much larger inefficiency than allocating too many permits.

This pattern of damage costs might be associated with a pollutant like methyl mercury, which can cause serious nerve damage above a low tolerance threshold. In this case, a quantity-based control system would be a more effective policy. If we allocate slightly too few or too many permits, the inefficiency will be relatively small. However, a small error in a pollution tax could result in large inefficiency and a very high pollution level.

A contrasting case occurs when the marginal damage curve is relatively flat, but the marginal reduction cost curve is steep, as shown in Figure 8.9. Here, pollution reduction costs rise rapidly, while per-unit damage is fairly stable.

In this case, quantity controls pose the more serious risk of error. The ideal quantity control would be at Q^*, but an excessively strict control at Q_1 would cause a rapid rise in marginal control costs, to T_1, with net social loss shown by areas (A + B). But a tax policy could deviate from the appropriate level of T^* without having much negative effect either in excessive cost or excessive damage. For example, the impact of a tax policy with a tax level set too high at T_2 causes only a small deviation from the Q^* level, with net social losses equal to the small triangle of area A.

Figure 8.9 **Pollution Regulation under Uncertainty with Steep Marginal Reduction Costs**



Industry spokespeople often argue that excessively rigid government regulations force high control costs for limited benefits. As we have seen, these arguments sometimes amount to crying wolf. But in cases where industry-wide control costs may genuinely be high, the use of a tax or pollution charge will allow firms to make their own decisions about pollution control. They will not be forced to undertake per-unit pollution reduction expenditures that are higher than the tax level, since they always have the option of paying the tax instead of reducing pollution. At the same time, the tax will require them to take account of the internalized social costs of pollution. For example, a tax on fertilizer or pesticides could encourage farmers to seek more environmentally-friendly production techniques while allowing the use of chemical inputs where they are cost-effective.

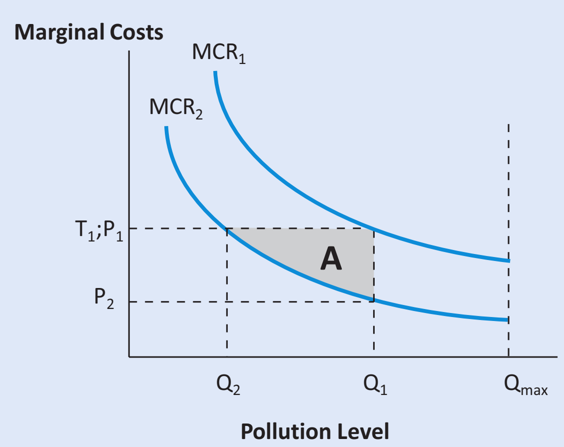
The Impact of Technological Change

When considering the effectiveness of different policies, we should also evaluate their relationship to technological progress in pollution control. The marginal reduction cost curves that we have used in our analysis are not fixed over time. With technological progress, control costs can be reduced. This raises two issues. First, how will changing control costs affect the policies that we have discussed? Second, what incentives do these policies create for the development of improved pollution control technologies?

Figure 8.10 shows how the level of pollution control will vary with different policies and technological change. Suppose that we start with control costs of MCR_1 and an initial pollution level of $Q_{max.}$ A pollution tax at the level T_1 will lead to reduction of pollution to the level Q_1. A permit allocation of Q_1 permits will have the same effect, with a market-determined permit price of P_1. Now suppose that technological progress lowers control costs to MCR_2. How will firms react?

In the pollution tax case, firms will have an incentive to increase pollution control, reducing pollution levels to Q_2. By doing so they save area A (the difference between the new control costs and the pollution taxes that they were formerly paying on units Q_1 to Q_2). With a permit system, however, the result will be different. Given the lower control costs, the

Figure 8.10 The Impact of Technological Change



permit price will fall to P_2. (Recall from Figure 8.5 that the equilibrium permit price is based on each firms' marginal reduction costs.) The total units of pollution reduced will remain the same at Q_1—equal to the total number of permits issued.

In fact, the permit system may have a seemingly perverse effect. If control costs fall drastically for some firms (those using newer technology), the permit price will fall, allowing plants with older technology to purchase more permits and actually increase emissions. This surprising effect of better pollution control technology leading to *more* pollution by some firms could, however, be avoided by reducing the total number of permits issued.

Both a pollution tax and a permit system create an incentive for technological improvement. But with a permit system regulators need to adjust the number of permits to account for changing technology. Since the level of a pollution tax is based on the marginal damage of pollution, it does not need to be adjusted as technology changes.

With a pollution standard, firms have an incentive to invest in technologies that may allow them to meet the standard at a lower cost, but they do not have a strong incentive to pursue technologies that may result in pollution levels below the standard. Finally, as mentioned previously, with a technology-based standard firms have little incentive to research new technologies, especially if these require higher costs.

Structuring Pollution Control Policies

A few other issues in designing pollution control policies are worth mentioning. First, under a tradable permit system there are two main ways in which to allocate permits. The first approach is to issue permits at no cost to existing firms, usually based on historical emissions. Obviously, polluting firms tend to prefer this approach because they receive something of value (the permits) at no charge. Yet by giving away the permits for free, the government misses an opportunity to raise revenues. Basing allocations on past emissions may also unfairly reward inefficient plants. Also, new firms, potentially with more efficient technologies, would be at a disadvantage because they would need to purchase permits on the open market from existing firms.

The second approach is a **permit auction**, in which permits are sold to the highest bidders. This has the advantage of bringing in government revenues that could be used to repair existing environmental damage or to lower taxes elsewhere in the economy. Tradable permits sold at auction would theoretically raise the same amount of revenue as an equivalent pollution tax. Under an auction, existing firms would not have an advantage over new firms.

A related issue is **grandfathering** of existing plants. This refers to a system in which strict pollution control regulations are applied to new plants, but existing plants are allowed to comply with less-demanding standards (or no standards at all). This is intended to avoid excessively high marginal control costs, but is clearly biased toward existing plants and is open to abuse. In particular, firms may have little incentive to close or update inefficient grandfathered plants and replace them with new plants that would face stricter, and more expensive, pollution regulations. For example, in 1977 amendments to the Clean Air Act exempted older power plants from certain air pollution requirements until such time as the plants undertook "major modifications." Unsurprisingly, owners of older plants often postponed technological improvements as long as possible.

permit auction a system that allocates pollution permits to the highest bidders.

grandfathering the process of exempting existing industrial facilities from complying with new environmental standards or regulations.

upstream policy a policy to regulate emissions or production as near as possible to the point of natural resource extraction.

When market-based policy instruments are used (i.e., taxes and tradable permits), an **upstream policy** is generally preferable. This means that the tax or permit applies as far upstream in the production process as possible, in order to minimize the administrative complexity of the policy. For example, consider levying a tax on petroleum. A downstream tax would require collecting the tax from over 120,000 gas stations in the United States.[13] But an upstream tax, at the refinery level, would require obtaining the tax from only about 140 oil refineries in the United States.[14]

Finally, issues of monitoring and enforcement must be considered when designing pollution control policies. Monitoring of emissions must be conducted to ensure compliance under policies of taxes, standards, and tradable permits. Monitoring is less critical with technology-based approaches, although inspections may be necessary to ensure that equipment is properly installed and operating. Major air and water pollution sources are increasingly being monitored using electronic equipment that provides continuous data on emissions. Facilities are also monitored using site visits from regulators, which can include interviews, review of records, collecting samples, and observing operations.

Regardless of which policy approach is taken, the punishments must be sufficient to deter violations. For example, the fine for emitting a unit of pollution without a permit should be substantially larger than the cost of a permit. In 2015 the U.S. EPA levied penalties in

Table 8.2 Summary of Characteristics of Pollution Policy Approaches

	Pollution Standards	Technology-Based Approaches	Pollution Taxes	Tradable Permit System
Is policy economically efficient?	No	No	Yes	Yes
Does policy create an incentive for innovation?	Only for meeting the standard	Generally no	Yes, resulting in lower pollution	Yes, resulting in lower permit price
Does policy require monitoring?	Yes	Minimal	Yes	Yes
Does policy generate public revenues?	No	No	Yes	Yes, if permits are auctioned
Does policy provide direct control over pollution levels?	Yes	No	No	Yes
Can policy eliminate hotspots?	Yes, if localized standards	Yes	No	No
Other advantages of policy?	Allows for flexibility in meeting standards	Can lead to lower costs for the best available control technology	Revenues can be used to lower other taxes	Individuals or organizations can buy and retire permits
Other disadvantages of policy?	Possibly no incentive to go beyond the standard	Doesn't allow for flexibility	Taxes generally politically unpopular	Permit system can be difficult to understand

over 1,000 civil cases, requiring environmental projects and payment of fines valued at over $7 billion. The EPA also brought criminal charges against 185 defendants in 2015, resulting in $200 million in fines and jail time for some individuals.[15]

Summarizing the Advantages and Disadvantages of Pollution Control Policies

The most appropriate pollution control policy depends upon the circumstances. While pollution taxes and tradable permits are generally preferred by economists because they are efficient (i.e., achieving a given level of pollution reduction for the least cost), there are situations when these policies might not be the best choices. Table 8.2 summarizes some of the main characteristics of each of the four policy options.

We have already discussed some of these characteristics, such as economic efficiency, the incentive for innovation, and monitoring. With standards and tradable permits, the government can set a cap on total emissions. With technology-based approaches and taxes, the resulting pollution level will be unknown in advance. Thus if the policy objective is to keep pollution levels below a known level with certainty, standards and permits may be the best options. But if encouraging innovation and minimizing control costs are major objectives, a pollution tax may be preferable.

Enacting pollution taxes can be politically difficult, especially in the United States, where new taxes are normally unpopular. In theory, a pollution tax can be **revenue-neutral** if the revenues from the tax are offset by lowering other taxes—but this may or may not occur in practice. Tradable permit systems tend to be more politically popular, especially if firms believe they can lobby policy makers to receive free permits. But a system of free permit allocations can result in a large transfer from consumers (who will pay higher prices) to companies that receive the valuable permits. If the permits are fully auctioned, however, the government can use the auction revenues to compensate ratepayers, or to lower other taxes.

revenue-neutral (tax policy) term used to describe a tax policy that holds the overall level of tax revenues constant.

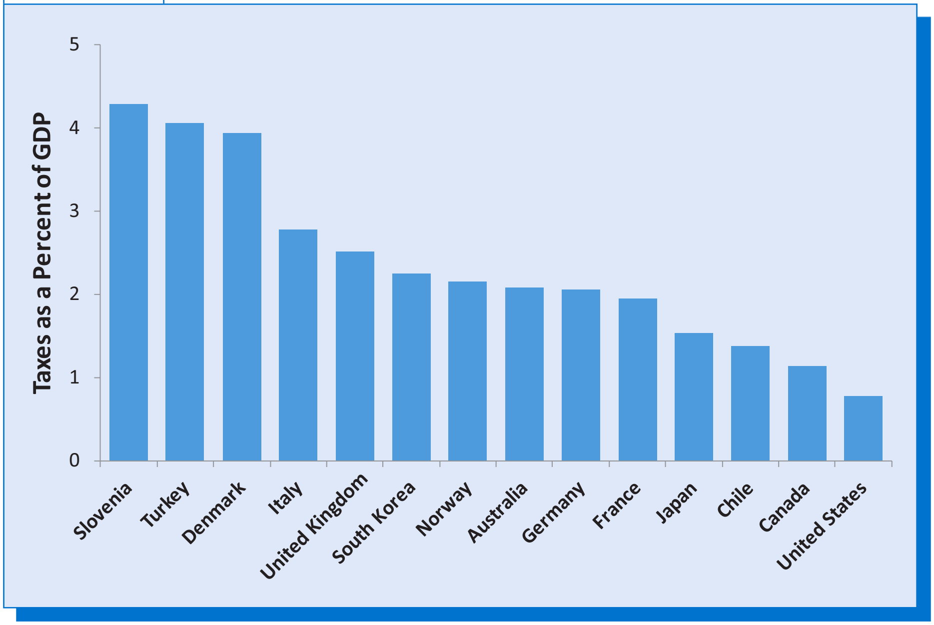
8.5 POLLUTION CONTROL POLICIES IN PRACTICE

In this section, we look at policies that have been enacted to regulate pollution, with a focus on the United States. Early pollution regulations in the 1960s and 1970s primarily used standards and technology-based approaches. Market-based approaches have become more common in recent years, particularly in policy responses to acid rain and global climate change.

Countries obviously vary in the stringency of their environmental policies. While it is conceptually difficult to compare pollution policies across countries, one measure that has been used to compare policies is the degree of environmental taxation across countries. Figure 8.11 shows environmental tax revenue in several countries that are members of the Organization for Economic Cooperation and Development (OECD), measured as a percentage of the gross domestic product (GDP).

Countries with relatively large environmental tax revenues include Slovenia, Denmark, Italy, and the United Kingdom. Each of these countries have environmental tax revenues above 2 percent of their GDP. Among developed countries, environmental taxes as a

Figure 8.11 Environmental Tax Revenues as a Percentage of GDP, Selected OECD Countries, 2013



Source: OECD, 2015, Table 2.7.

percent of GDP are lowest in the United States. However, we should not necessarily conclude that the United States has the laxest environmental policies, as we need to consider other policy instruments, such as standards and technology-based policies. In fact, local air pollution levels in the United States are more than 20 percent lower than the OECD average.[16] We now consider in more detail the pollution control policies of the United States.

Air Pollution Regulation

The major federal law governing air quality in the United States is the **Clean Air Act** (CAA), first passed in 1970 and significantly revised in 1990.[17] The goal of the CAA is to set regional air pollution standards to protect human health with an "adequate margin of safety."[18] The Act specifies that standards are to be set based on the best scientific evidence, explicitly ruling out cost-benefit analysis. The standards may be adjusted over time as more information becomes available.

criteria air pollutants the six major air pollutants specified in the U.S. Clean Air Act.

The CAA divides air pollutants into two categories. The first category includes six major or **criteria air pollutants**: particulate matter, ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead. Atmospheric concentrations of the criteria pollutants have declined substantially since the passage of the CAA, with an aggregate decrease of 69 percent between 1970 and 2014.[19] The decline in lead has been particularly dramatic; lead concentrations have declined 97 percent, primarily as a result of banning leaded gasoline. Despite this progress, more than 57 million Americans live in counties where the criteria pollutant standards were exceeded in 2014, mainly due to high ground-level ozone concentrations (also known as smog).

The 1990 CAA Amendments established a tradable permit system to address acid rain. The original objective of the permit system was to reduce emissions of sulfur dioxide (SO_2) by 50 percent by 2010, compared to 1980 levels.[20] The program is widely considered a success, with a decline in SO_2 emissions of 76 percent over 1990–2014 and costs significantly lower than expected (for more on the SO_2 trading program, see Box 8.2).

The second category of pollutants regulated by the CAA is **toxic air pollutants**. These pollutants are emitted in smaller quantities but cause dangerous health effects such as cancer, birth defects, and respiratory damage. Examples of toxic air pollutants include mercury, arsenic, and vinyl chloride. Initial progress on addressing toxic air pollutants was slow, but the 1990 CAA Amendments directed the EPA to establish technology-based regulations for large sources emitting one or more of nearly 200 toxic air pollutants. The EPA has issued rules regulating more than 80 major industrial sources, such as chemical plants, oil refineries, and steel mills. These regulations have reduced toxic air pollution from large sources by more than about 70 percent, although further regulations are still needed for smaller sources and to address the complete list of toxic air pollutants. An assessment of toxic air pollutants published by the EPA in 2015 concluded that approximately one in every 25,000 people in the U.S. have an increased likelihood of contracting cancer as a result of inhaling toxic air pollutants.[21] Chemicals with the largest impacts include formaldehyde and benzene.

toxic air pollutants harmful air pollutants other than the six criteria pollutants, as specified in the U.S. Clean Air Act.

Water Pollution Regulation

The main federal law regulating surface waters in the United States is the **Clean Water Act (CWA)**, passed in 1972 and amended in 1977. The CWA set very ambitious goals: to make all the country's lakes and rivers safe for fishing and swimming by 1983 and to eliminate all discharges of pollutants into navigable waters by 1985. While progress has been made, none of these goals have been attained, even now. For example, a 2007 assessment of the country's lakes found that 56 percent were rated as "good," 21 percent as "fair," and 22 percent as "poor."[22] The ecological condition of rivers and streams also demonstrates the need for further improvements. According to the EPA's National Rivers and Streams Assessment, 46 percent of the nation's rivers are in poor biological condition, 25 percent are in fair condition, and only 28 percent are in good condition. The assessment notes that more than 40 percent of the nation's rivers suffer from excess nutrient loading. High concentrations of phosphorus and nitrogen, used as agricultural fertilizers, can lead to algal blooms which result in reduced oxygen levels and mortality of aquatic animals and plants.[23]

Clean Water Act (CWA) the primary federal water pollution law in the United States, passed in 1972.

The CWA primarily focused on **point-source pollution**—pollution from a definite source such as a drainpipe. The CWA relies upon both standards and technology-based approaches to regulate point sources. For example, it directs the EPA to specify the "best available technology" for various types of facilities. The most significant progress has been made in reducing industrial discharge. Major point sources of pollution must receive a permit to

point-source pollution pollution that is emitted from an identifiable source, such as a smokestack or waste pipe.

ensure they are in compliance with the CWA and report discharge to the EPA.

The original CWA did not address **nonpoint-source pollution**—pollution from sources such as stormwater and agricultural runoff. Because of the diffuse nature of nonpoint source pollution, it is more difficult to control. Subsequent legislation has primarily placed the responsibility for regulating nonpoint-source pollution with the individual states, although the EPA has established numerous guidelines, such as suggested measures to limit runoff pollution from agriculture, forestry, and urban areas.

nonpoint-source pollution pollution that is difficult to identify as originating from a particular source, such as groundwater contamination from agricultural chemicals used over a wide area.

Other Pollution Regulation

Other pollution regulation focuses on hazardous wastes and chemicals. The **Resource Conservation and Recovery Act (RCRA)** was enacted in 1976 to regulate the disposal of hazardous wastes. Under the RCRA, the EPA has designated hundreds of chemicals as hazardous, not just because of toxicity but also for other reasons such as corrosiveness and flammability. The RCRA requires "cradle-to-grave" tracking of hazardous materials, including any transportation of materials. It also sets safety standards for facilities that treat, store, or dispose of hazardous materials. The RCRA has been effective in reducing hazardous waste generation, which declined from about 300 million tons annually in the 1970s to 35 million tons in 2013.[24]

Resource Conservation and Recovery Act (RCRA) the primary federal U.S. law regulating the disposal of hazardous waste.

Regulation of other chemicals in the United States is covered under the **Toxic Substances Control Act (TSCA)**, passed in 1976. The Act gives the EPA the authority to review the safety of new chemicals and restrict the use of existing chemicals. Unlike most other major pollution laws, the TSCA does direct the EPA to consider economic costs and benefits explicitly when evaluating chemicals. For existing chemicals (those already in use before 1980) the burden of proof is on the EPA to prove that a chemical poses an "unreasonable risk." This essentially grandfathered the use of 62,000 chemicals, in most cases without information about potential health and environmental impacts. As of 2015 the EPA has required testing of only about 250 existing chemicals and regulated only five.[25]

Toxic Substances Control Act (TSCA) the primary federal U.S. law regulating the use and sale of toxic chemicals.

The TSCA is more stringent in regulating new chemicals. The EPA must be notified when a new chemical is to be produced, providing time for the EPA to review the potential risks of the chemical. However, even then it is up to the EPA to request testing from the manufacturer, which is normally not done. Of the approximately 40,000 new chemicals submitted to the EPA under the TSCA, about 10 percent have been subject to regulatory action such as additional testing or restrictions.[26]

In contrast to the United States, the European Union has enacted a significantly more powerful chemical policy that embodies the **precautionary principle**. Called REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals), the policy places the burden of proof on chemical manufacturers to prove the safety of their chemicals (for more details on REACH, see Box 8.3).

precautionary principle the view that policies should account for uncertainty by taking steps to avoid low-probability but catastrophic events.

Box 8.3 EUROPEAN CHEMICALS POLICY

The European Union's ambitious chemicals policy, REACH, went into effect in 2007, and is being phased in over an 11-year period. According to the EU's web site for REACH, one of the "main reasons for developing and adopting the REACH Regulation was that a large number of substances have been manufactured and placed on the market in Europe for many years, sometimes in very high amounts, and yet there is insufficient information on the hazards that they pose to human health and the environment. There is a need to fill these information gaps to ensure that industry is able to assess hazards and risks of the substances, and to identify and implement the risk management measures to protect humans and the environment."

Unlike TSCA, REACH applies the same safety standards to new and existing chemicals. Another difference is that the burden of proof regarding a chemical's safety is on the chemical manufacturers, not the regulating agency. If a manufacturer cannot demonstrate the safety of the chemical, its use may be restricted or banned.

Multiple manufacturers of the same chemical may join together to reduce the costs of testing. In addition to requiring testing for all new chemicals, REACH requires manufacturers to provide test results for existing chemicals. The initial focus has been on testing those chemicals produced in high volumes (greater than 1,000 metric tons per year) or of the greatest concern. By 2018 all chemicals produced in excess of one metric ton annually will need to meet REACH's requirement that the chemical be registered, evaluated for safety, and approved for manufacture. REACH's requirements apply to all chemicals produced in or imported into the EU. As of 2016, 168 chemicals have been identified as "substances of very high concern." These chemicals must be authorized under REACH for each specific use.[27]

The EU has estimated the costs of complying with REACH to be €2.8 to €5.2 billion ($3.6 to $6.7 billion) over 11 years. If the program reduces chemical-related diseases by 10 percent, the estimated benefits would be about €50 billion ($65 billion) over 30 years, a benefit/cost ratio of 10:1. An independent economic analysis of REACH concludes:

> Ultimately, REACH will provide the long-term benefit of helping to create sustainable industry and a healthy environment in Europe. As other parts of the world move to adopt similar standards in the future, European industry will gain the competitive advantage that comes from being the first to move toward cleaner and safer production and use of chemicals. (Ackerman and Massey, 2004, p. 12)

Sources: European Commission, 2006; Ackerman and Massey, 2004.

Summary

The principle of economic efficiency in environmental policy implies a balance between the marginal costs of pollution reduction and the marginal damage of pollution. This has implications for both the level of control and the policies used to achieve it. Although the principle of balancing marginal costs and benefits is simple in theory, its application to real-world issues is often complex and involves judgment about both goals and policies.

Pollution levels can be regulated in four basic ways. The most commonly used approaches have been to set pollution standards and mandate certain technologies. While these two policies have certain advantages, economists tend to prefer market-based approaches, such as pollution taxes and tradable permit systems. With a pollution tax, the tax level should reflect the damage caused by the pollution. A pollution tax allows individual firms to decide how much pollution reduction to undertake. Least-cost pollution control options will be selected first. However, choosing the tax level requires an accurate estimate of damage costs, which may be difficult to determine in monetary terms.

Tradable pollution permits allow the setting of a target for total pollution reduction. The permit price is then set through the market mechanism, as firms trade permits. This, in theory, combines the advantages of a definite amount of pollution reduction with an economically efficient process. But it is only best suited for specific pollution control efforts under particular conditions, and may not be appropriate in all cases.

Market-based policies often fail to control pollutants that exhibit nonlinear and threshold damage effects, as well as pollutants with local rather than regional impact. Specific emissions standards may be needed for these pollutants, especially those that produce potentially severe health or ecological damage. Important considerations in the choice of pollution policy include the patterns of costs and damage as well as options for improved pollution-control technology. Policies should be selected with a view toward minimizing unnecessary costs or damage and promoting technological progress in pollution control.

Pollution policies in practice have led to major pollution reduction in some cases, but not in others. In the United States, emissions of criteria air pollutants have been significantly reduced since the 1970s, and progress has been made in reducing toxic pollutants. Water pollution policies have reduced point source pollution, with less progress on addressing non-point source pollution. For potentially toxic chemicals, the burden of proof in the United States is on regulators to determine whether a chemical is safe. Meanwhile, recent chemicals policy in the European Union places the burden of proof on manufacturers to demonstrate a chemical's safety.

Key Terms and Concepts

best available control technology

Clean Air Act (CAA)

Clean Water Act (CWA)

command-and-control policies

criteria air pollutants

cumulative pollutants

emissions standards

equimarginal principle

flow pollutants

global climate change

grandfathering

hotspots

internalizing external costs

local, regional, and global pollutants

market-based approaches

nonlinear or threshold effects

non–point-source pollution

nonuniformly mixed pollutants

optimal level of pollution

permit auction

Pigovian (pollution) taxes

point-source pollution

pollution standards

pollution taxes

precautionary principle

regulation

Resource Conservation and Recovery Act (RCRA)

revenue-neutral

sink function

stock pollutants

technology-based approaches

technology-based regulation

toxic air pollutants

Toxic Substances Control Act (TSCA)

tradable pollution permits

uniformly mixed pollutants

upstream policy

Discussion Questions

1. How practical is the idea of an optimal pollution control level? How is it possible to establish such a level in practice? Can this be done solely based on economic analysis, or do other factors have to be taken into account?
2. Suppose that your state has a problem with pollution of rivers and lakes, from both residential and industrial sources. You are asked to advise on appropriate pollution control policies. Which kinds of policies would be appropriate? How would you decide whether to recommend standards, technology-based approaches, pollution taxes, permits, or another policy? What factors (e.g., different kinds of pollution) would affect your decision?
3. Why is a freeze on emissions not an adequate policy response to a cumulative pollutant such as chlorofluorocarbons? What kinds of policies are more appropriate, and why is it often especially difficult to implement these policies?
4. What stories have you seen in the news recently regarding pollution policies? Considering the information that you have learned in this chapter, what are your policy recommendations in these cases?

Exercise

Two power plants are currently emitting 8,000 tons of pollution each (for a total of 16,000 tons). Pollution reduction costs for Plant 1 are given by $MCR_1 = 0.02Q$ and for Plant 2 by $MCR_2 = 0.03Q$, where Q represents the number of tons of pollution reduction.

a) Suppose a regulation is implemented that requires each plant to reduce its pollution by 5,000 tons. What will be each firm's pollution control costs? Draw two graphs (one for each firm) to support your answer, similar to Figure 8.4.

b) Suppose instead that a pollution tax of $120 per ton of pollution emitted is implemented. How much will each firm now pay in pollution reduction costs (not considering taxes)? How do total pollution reduction costs with the tax compare to the total costs from part (a)? Briefly explain why the costs differ. How much does each firm pay in taxes? Use two graphs (one for each firm) to support your answer, similar to Figure 8.4.

c) Finally, suppose a tradable permit system is instituted in which permits for emissions of 6,000 tons of pollution are freely issued, 3,000 permits to each plant. What are the pollution reduction costs to each firm without trading? Use a graph similar to Figure 8.5 to support your answer, showing 10,000 tons of total pollution reduction.

d) Using the same diagram you drew in part (c), explain which firm will sell permits (and how many), and which firm will buy permits. Assuming all permits sell for the same price, how much will each permit cost? Calculate each firm's net costs after trading, considering their pollution reduction costs and the costs (or revenues) from the permit sale.

Notes

1. Note that firms could also reduce pollution by simply producing less. We can assume firms will take the most cost-effective steps to reduce pollution, either by maintaining production levels but with lower pollution levels, or by reducing production and forgoing potential profits.
2. The equimarginal principle can also apply to marginal reduction costs for different firms or different techniques, as we will see in our discussion of pollution control approaches. Tietenberg and Lewis, 2011, distinguish between the "first equimarginal principle" of equating marginal costs and marginal benefits at the overall social level and the "second equimarginal principle" of equalizing marginal reduction costs among firms.
3. Some economists refer to government-set standards as command-and-control systems, comparing them unfavorably to market-based mechanisms. We avoid this terminology here, since it may convey unnecessary bias. Rather, we seek to evaluate different policies on their merits, without preconceptions as to which is better. Goodstein, 2010, chap. 14, shares this reservation about the use of the term.
4. Various other terms are used to describe the "best" technology, including "best available technology" (BAT), "reasonable available control technology" (RACT), and "maximum available control technology" (MACT).
5. Clean Water Act section 301(b), 33 U.S.C. § 1311(b).
6. Tietenberg and Lewis, 2011, refer to this as the "second equimarginal principle."
7. For an in-depth account of the background and implementation of the 1990 Clean Air Act, see Goodstein, 2010, chaps. 14 and 17.
8. In mathematical terms, Total Cost = TC = ∫ [0 to *q*] *MC dq*, where *q* is units of pollution reduced.
9. In the case of leaded gasoline, the pollution is spread widely through automobile exhaust, and in this case lead becomes a regional pollutant.
10. Sanchez, 1998, discusses how the Clean Air Act promoted technological progress in emissions reduction; Joskow *et al.*, 1998, and Stavins, 1998, examine the operation of the market for emissions rights. Burtraw *et al.*, 1998, finds that Clean Air Act Amendments benefits considerably outweigh costs, and Jorgenson and Wilcoxen, 1998, evaluate the act's overall economic impact.
11. Global emissions of CFCs have not actually reached zero, but have declined over 90 percent since peaking in the late 1980s.
12. In mathematical terms, this relationship can be expressed as $A = \int e\, dt$, meaning that accumulation can be measured as the integral of emissions over time.
13. Number of gas stations from the U.S. Census Bureau.
14. Number of refineries from the Energy Information Agency (EIA).
15. Information from U.S. EPA, "Enforcement Annual Results Numbers at a Glance for Fiscal Year (FY) 2015," https://www.epa.gov/enforcement/enforcement-annual-results-numbers-glance-fiscal-year-fy-2015.
16. Based on particulate matter (PM2.5) concentrations for 2013; data from the World Bank, World Development Indicators database, http://data.worldbank.org.
17. A Clean Air Act was passed by Congress in 1963, but this law only established funding to address air pollution, without any standards or other direct efforts to reduce pollution.
18. Information for this section is based on Goodstein, 2010, and U.S. Environmental Protection Agency, 2007.
19. https://www3.epa.gov/airtrends/images/y70_14.png
20. U.S. Environmental Protection Agency, 2002.

21. U.S. Environmental Protection Agency, 2015.
22. U.S. Environmental Protection Agency, 2010.
23. U.S. Environmental Protection Agency, 2016.
24. U.S. Environmental Protection Agency online Biennial Hazardous Waste Report Summary, https://rcrainfo.epa.gov/rcrainfoweb/action/modules/br/national/view.
25. Center for Effective Government, 2015.
26. U.S. Environmental Protection Agency. Statistics for the New Chemicals Review Program under TSCA, https://www.epa.gov/reviewing-new-chemicals-under-toxic-substances-control-act-tsca/statistics-new-chemicals-review.
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Web Sites

1. **www.epa.gov/airmarkets/.** The EPA's web site for tradable permit markets for air pollutants, including links to extensive information about the SO_2 emissions trading program.
2. **www.rff.org/home.** Web site of Resources for the Future, featuring many publications on the benefits of pollution reduction and different approaches for regulating pollution.
3. **http://ec.europa.eu/environment/chemicals/reach/reach_en.htm.** The European Union's web site for REACH, including Fact Sheets, background documents, and updates on the process of implementing REACH.
4. **www.edf.org/approach/markets/.** Environmental Defense Fund web site on using economic incentives to improve environmental quality, with links to articles and videos.

PART

III

Ecological Economics and Environmental Accounting

CHAPTER 9

Ecological Economics: Basic Concepts

Chapter 9 Focus Questions

- Are natural resources a form of capital?
- How can we account for and conserve resources and environmental systems?
- What limits the scale of economic systems?
- How can we sustain economic well-being and ecosystem health in the long term?

9.1 AN ECOLOGICAL PERSPECTIVE

The relationships between economic and environmental issues can be viewed from a variety of perspectives. In Chapters 3–8 we applied concepts derived from standard economic analysis to environmental issues. The school of thought known as **ecological economics**, however, takes a different approach. Ecological economics attempts to redefine basic economic concepts to make them more applicable to environmental problems. As noted in Chapter 1, this often means viewing problems from a macro rather than a micro perspective, focusing on major ecological cycles and applying the logic of physical and biological systems to the human economy, rather than viewing ecosystems through a lens of economic analysis:

methodological pluralism the view that a more comprehensive understanding of problems can be obtained using a combination of perspectives.

> The fundamental, original premise of ecological economics is to insist on seeing the human economy as embedded in and part of Earth's biogeochemical systems.[1]

Unlike standard economic analysis, ecological analysis does not have a single methodological framework based on markets. Ecological economist Richard Norgaard has identified this approach as **methodological pluralism**, maintaining that "multiple insights guard against mistaken action based on one perspective."[2] ("Methodology" means the set of techniques and approaches used to analyze a problem.) Through a combination of different analyses and techniques, we can achieve a more comprehensive picture of the problems that we study.

This pluralist approach means that ecological economics is not necessarily incompatible with standard market analysis. The analyses reviewed in Chapters 3–8 offer many insights that are complementary to a broader ecological perspective. But some of the assumptions and concepts used in market analysis may need to be modified or replaced in order to gain an understanding of the interaction between the economic system and ecological systems.[3]

9.2 NATURAL CAPITAL

One fundamental concept emphasized by ecological economists is **natural capital**. Most economic models of the production process focus on two factors of production: capital and labor. A third factor, usually referred to as "land," is acknowledged but usually has no prominent function in economic models. Classical economists of the nineteenth century, especially David Ricardo, author of *The Principles of Political Economy and Taxation*, were concerned with land and its productivity as a fundamental determinant of economic production.[4] Modern economics, however, generally assumes that technological progress will overcome any limits on the productive capacity of land.

natural capital the available endowment of land and resources, including air, water, soil, forests, fisheries, minerals, and ecological life-support systems.

Ecological economists have reintroduced and broadened the classical concept of "land," renaming it natural capital. Natural capital is defined as the entire endowment of land and resources available to us, including air, water, fertile soil, forests, fisheries, mineral resources, and the ecological life-support systems without which economic activity, and indeed life itself, would not be possible.

In an ecological economics perspective, natural capital should be considered at least as important as human-made capital as a basis for production. Further, a careful accounting should be made of the state of natural capital and of its improvement or deterioration, and this should be reflected in national income accounting.

Accounting for Changes in Natural Capital

net investment and disinvestment the process of adding to, or subtracting from, productive capital over time, calculated by subtracting depreciation from gross, or total, investment.

Defining natural resources as capital raises an important economic implication. A central principle of prudent economic management is preservation of the value of capital. It is generally desirable to add to productive capital over time, a process that economists call **net investment**. A country whose productive capital decreases overtime (**net disinvestment**) is a country in economic decline.

Sir John Hicks, Nobel laureate in economics and author of *Value and Capital* (1939), defined income as the amount of goods and services that an individual or country can consume over a period while remaining at least as well off at the end of the period as at the beginning. In other words, you cannot increase your income by reducing your capital.

To see what this means in practice, imagine someone who receives an inheritance of $1 million. Suppose that the $1 million is invested in bonds that yield a real return (i.e., return in excess of inflation) of 3 percent. This will give an annual income of $30,000. However, if the recipient of the inheritance decides to spend $50,000 per year from the inheritance, s/he will be spending $20,000 of capital in addition to the $30,000 income. This means that in future years, the income will be reduced, and eventually the capital will be entirely depleted. Clearly, this is different from a prudent policy of living only on income, which would allow the recipient to have an income of $30,000 per year indefinitely.

This principle is generally accepted insofar as human-made capital is concerned. Standard national income accounting includes a calculation of the depletion of human-made capital over time. This **capital depreciation** is estimated annually and subtracted from gross national product to obtain net national product. To maintain national wealth undiminished requires at least enough investment to replace the capital that is depleted each year. We recognize this also by distinguishing between gross and net investment. Net investment is gross investment minus depreciation and can be zero or below zero if insufficient replacement investment occurs. A negative net investment implies a decline in national wealth.

capital depreciation a deduction in national income accounting for the wearing-out of capital over time.

natural capital depreciation a deduction in national accounting for loss of natural capital, such as a reduction in the supply of timber, wildlife habitat, or mineral resources.

But no similar provision is made for **natural capital depreciation**. If a country cuts down its forests and converts them to timber for domestic consumption or export, this enters the national income accounts only as a positive contribution to income, equal to the value of the timber. No accounting is made of the loss of standing forest, either as an economic resource or in terms of its ecological value. From the standpoint of ecological economics, this is a serious omission that must be corrected.[5] Ecological economists have proposed revisions to national income accounting systems so as to include natural capital depreciation (we consider these proposals in detail in Chapter 10).

The Dynamics of Natural Capital

The natural capital concept further implies that a purely economic analysis cannot fully capture the stock and flow dynamics of natural resources. As we saw in Chapters 6 and 7, economists have many techniques for expressing natural resource and environmental factors in monetary terms suitable for standard economic analysis. But this captures only one dimension of natural capital.

The basic laws governing behavior of natural capital elements such as energy resources, water, chemical elements, and life forms are physical laws described in the sciences of chemistry, physics, biology, and ecology. Without specific consideration of these laws, we cannot gain a full understanding of natural capital.

For example, in agricultural systems, soil fertility is determined by complex interactions among chemical nutrients, micro-organisms, water flows, and plant and animal waste recycling. Measuring soil fertility in terms of, say, grain output, will be valid for short-term economic calculations, but may be misleading over the long term as subtler ecological processes come into play. Loss of micronutrients, carbon content, and water retention capacity over time could result in a steady decline in underlying soil fertility, which might go unnoticed because it could be masked by application of more fertilizer in the short term. A purely economic analysis could result in insufficient attention to long-term maintenance of soil fertility.

Thus it is necessary to combine insights from economic analysis with ecological principles when dealing with issues of the maintenance of natural capital. This does not render the economic techniques of Chapters 3–8 irrelevant; rather, they must be complemented by ecological perspectives on natural systems to avoid misleading results. Techniques advocated by ecological economists for natural capital accounting and conservation include the following:

- Physical accounting for natural capital. In addition to the familiar national income accounts, satellite accounts can be constructed to show the abundance or scarcity of natural resources and to estimate their variations from year to year. These accounts can also show pollutant build-up, water quality, soil fertility variations, and other important physical indicators of environmental conditions. Accounts that indicate significant resource depletion or environmental degradation call for measures to conserve or restore natural capital.

- Determination of sustainable yield levels. As we saw in Chapter 4, economic exploitation of natural resources often exceeds ecologically sustainable levels. An ecological analysis of a natural system harvested for human use can help to determine the sustainable yield level at which the system can continue to operate indefinitely. If the economic equilibrium yield exceeds the sustainable yield, the resource is threatened, and specific protective policies are necessary. This has happened with many fisheries and forests, a topic dealt with in Chapters 18 and 19.

- Determination of the absorptive capacity of the environment for human-generated wastes, including household, agricultural, and industrial wastes. Natural processes can break down many waste products over time and reabsorb them into the environment without damage. Other waste and pollutants, such as chlorinated pesticides, chlorofluorocarbons (CFCs), and radioactive waste are difficult or impossible for the environment to absorb. In the case of carbon dioxide, there is a planetary capacity to absorb excess carbon, but this capacity is now being exceeded. In general, scientific analysis can offer a baseline estimate of acceptable levels of waste emissions. This will not necessarily coincide with the economic concept of "optimal pollution levels" introduced in Chapter 3, since it takes into account ecological factors that are not reflected in the market-based analysis of marginal costs and benefits.

physical accounting a supplement to national income accounting that estimates the stock or services of natural resources in physical, rather than economic, terms.

satellite accounts accounts that estimate the supply of natural capital in physical, rather than monetary, terms; used to supplement traditional national income accounting.

resource depletion a decline in the stock of a renewable resource due to human exploitation.

environmental degradation loss of environmental resources, functions, or quality, often as a result of human economic activity.

sustainable yield a yield or harvest level that can be maintained without diminishing the stock or population of the resource.

absorptive capacity of the environment the ability of the environment to absorb and render harmless waste products.

substitutability (of human-made and natural capital) the ability of one resource or input to substitute for another; in particular, the ability of human-made capital to compensate for the depletion of some types of natural capital.

complementarity the property of being used together in production or consumption, for example, the use of gasoline and automobiles.

natural capital sustainability conserving natural capital by limiting depletion rates and investing in resource renewal.

This perspective differs in significant respects from standard economic theory, which generally assumes **substitutability** between resources. For example, industrially produced fertilizer might compensate for loss of fertile soil. The ecological perspective tells us that substitution is not so easy—the natural resource base for economic activity is in a sense irreplaceable, unlike human-made factories or machinery. In the case of fertilizer, heavy applications of fertilizer can deplete other nutrients in the soil as well as pollute waterways with fertilizer runoff.

In many cases, natural capital displays **complementarity** rather than substitutability with manufactured capital—meaning that both are needed for effective production. For example, increasing the stock of fishing boats will be of no use if stocks of fish are depleted (as discussed in Chapters 4 and 13). The essential function of natural capital means that we need to modify standard theories of economic growth to take into account issues of ecological limits and long-term sustainability.[6]

This analysis points toward a general principle of **natural capital sustainability**. According to this principle, countries should aim to conserve their natural capital by limiting its depletion or degradation and investing in its renewal (e.g., through soil conservation or reforestation programs). The difficult and controversial process of translating this general principle into specific policy rules brings into focus the differences between economic and ecological analyses. We deal with some of these questions in more detail in future chapters.

9.3 ISSUES OF MACROECONOMIC SCALE

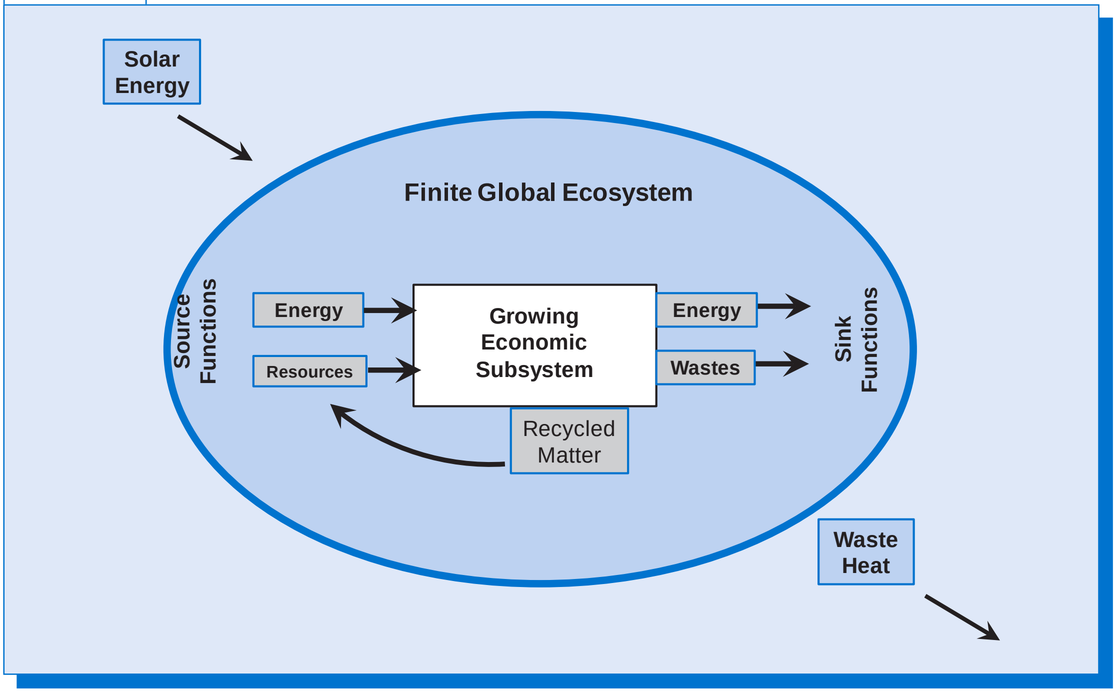
Standard macroeconomic theory recognizes no limitation on an economy's scale. Keynesian, classical, and other economic theories deal with the conditions for equilibrium among the macroeconomic aggregates of consumption, savings, investment, government spending, taxes, and money supply. But with economic growth, the equilibrium level can in theory rise indefinitely, so that a country's gross domestic product (GDP) can multiply tenfold or a hundredfold over time.

With a 5 percent growth rate, for example, GDP would double every fourteen years, becoming more than 100 times as large within a century. Even at a 2 percent growth rate, GDP doubles in 35 years, growing sevenfold in a century. From the point of view of mathematical computation of economic equilibrium, such growth poses no problem. But ecological economists, in particular Robert Goodland and Herman Daly, have argued that resource and environmental factors impose practical limits on feasible levels of economic activity and that economic theory must include a concept of **optimal macroeconomic scale**.[7]

optimal macroeconomic scale the concept that economic systems have an optimal scale level beyond which further growth leads to lower well-being or resource degradation.

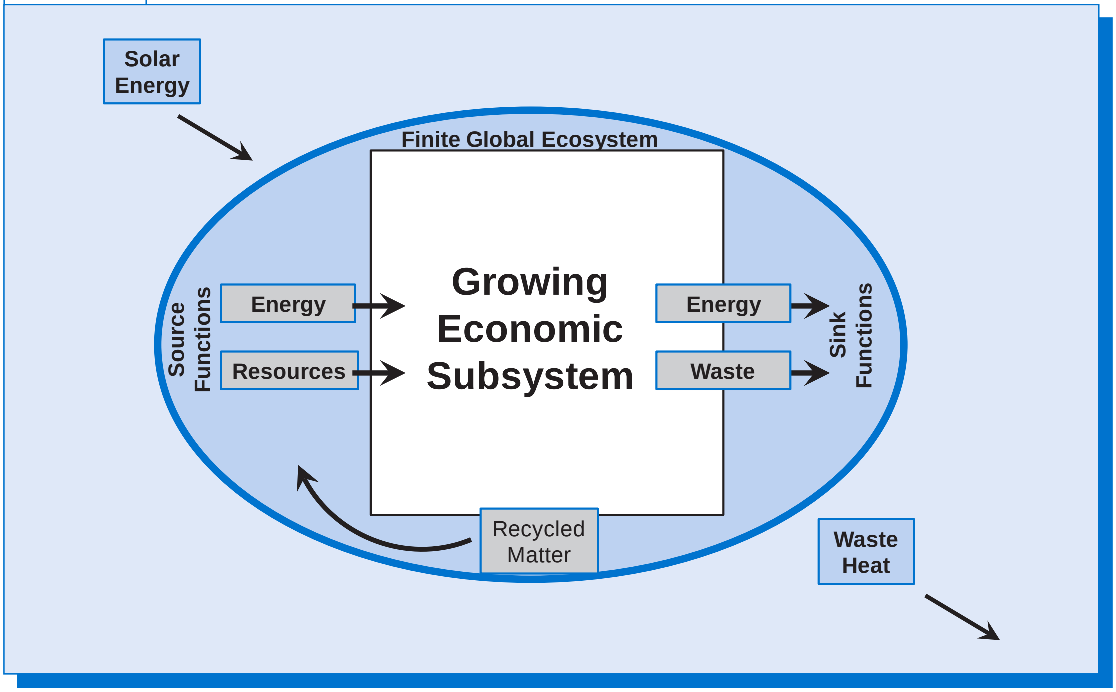
This concept is relevant both for individual economies dependent on limited resource bases and for the global economy. Its implications for the global economy are especially important, because national economies can overcome resource limitations through international trade. The situation is illustrated in Figures 9.1 and 9.2. Figure 9.1, showing a schematic relationship between economic and ecological systems, is similar to Figure 1.2 in Chapter 1. Figure 9.2 shows how the situation changes as the economy grows, with a larger economic subsystem applying significant physical and life-cycle stress on the surrounding ecosystem.

Figure 9.1 The Economic Subsystem Relative to the Global Ecosystem (Small Scale)



Source: Goodland, Daly, and El Serafy, 1992, p. 5.

Figure 9.2 The Economic Subsystem Relative to the Global Ecosystem (Large Scale)



Source: Goodland, Daly, and El Serafy, 1992, p. 5.

The economic system (shown as a rectangle in Figures 9.1 and 9.2) uses both energy and resources as inputs and releases waste energy and other wastes into the ecosystem (shown as a circle). The combined input and waste flows can be called **throughput**.[8] The economic system as shown here is an **open system**, exchanging energy and resources with the global ecosystem within which it is located. The global ecosystem has an inflow of solar energy and an outflow of waste heat, but is otherwise a **closed system**.

throughput the total use of energy and materials as both inputs and outputs of a process.

open system a system that exchanges energy or natural resources with another system; the economic system is considered an open system because it receives energy and natural resources from the ecosystem and deposits wastes into the ecosystem.

closed system a system that does not exchange energy or resources with another system; except for solar energy and waste heat, the global ecosystem is a closed system.

scale limit a limit to the size of a system, including an economic system.

empty-world and full-world economics the view that economic approaches to environmental issues should differ depending on whether the scale of the economy relative to the ecosystem is small (an empty world) or large (a full world).

steady state an economy that maintains a constant level of natural capital by limiting the throughput of material and energy resources.

dematerialization the process of achieving an economic goal through a decrease in the use of physical materials, such as making aluminum cans with less metal.

decoupling breaking the correlation between increased economic activity and similar increases in environmental impacts.

As the open economic subsystem grows within the closed planetary ecosystem (shown by the enlarged rectangle in Figure 9.2), its resource needs and waste flows are more difficult to accommodate. The fixed size of the planetary ecosystem places a **scale limit** on economic system growth.

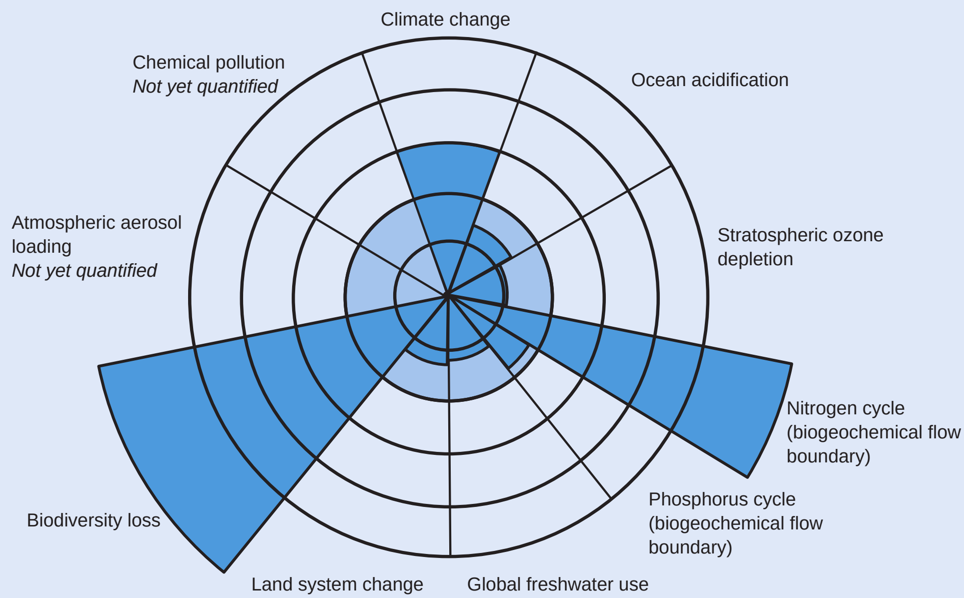
Daly and Goodland have argued that rapid economic growth brought us from **empty-world economics** to **full-world economics**. In the "empty-world" phase, when the economic system is small relative to the ecosystem, resource and environmental limits are unimportant, and the main economic activity is the exploitation of natural resources to build up human-made capital stocks and to expand consumption. At this stage, economic activity is constrained mainly by limited quantities of human-made capital.

In the "full-world" phase, however, when the dramatically expanded human economic system presses against ecosystem limits, the conservation of natural capital becomes far more important. If we do not implement adequate measures to conserve resources and protect the "full-world" environment, environmental degradation will undermine economic activity regardless of how large stocks of human-made capital become.[9] Ultimately, this implies that the economy must adapt from a pattern of growth to a **steady-state** in which population and production rates must stabilize:

> The facts are plain and incontestable: the biosphere is finite, non-growing, and closed (except for the constant input of solar energy). Any subsystem such as the economy, must cease growing at some point and adapt itself to a dynamic equilibrium, something like a steady state. To achieve this equilibrium, birth rates must equal death rates, and production rates of commodities must equal depreciation rates.[10]

This logic refers to the *physical* growth of the economic system, measured in terms of its resource and energy demands and waste flows. It is possible for GDP to grow without higher resource requirements, especially if growth is concentrated in the service sector. Expanded automobile production, for example, requires more steel, glass, rubber, and other material inputs, as well as gasoline to operate the vehicles. But more opera productions or child-care services require few physical resources. Energy and physical resource use may also become more efficient, thus requiring fewer throughputs of resources per unit of output, a process known as **dematerialization** or **decoupling**, discussed in greater detail in Chapter 14. In general, though, growing GDP is

Figure 9.3 Planetary Boundaries



Source: Rockström *et al.*, 2009.

Note: The inner shading represents the proposed "safe operating space" for nine planetary systems. The wedges represent an estimate of the current position for each system. The boundaries in three systems (rate of biodiversity loss, climate change, and human interference with the nitrogen cycle) have already been exceeded and two others (ocean acidification and phosphorous cycle) were close to limits as of 2009.

associated with higher throughput of energy and resources. Ecological economists, therefore, work to develop "a conceptual framework within which macroeconomic stability is consistent with the ecological limits of a finite planet."[11]

Economic activity undoubtedly faces some scale limits. How can we determine whether the economic subsystem is straining the limits of the ecosystem? One way is simply by noting the increased prevalence of large-scale or global environmental problems, such as global climate change, ozone layer destruction, ocean pollution, soil degradation, and species loss.[12] In commonsense terms as well as in ecological analysis, these pervasive problems suggest that important environmental thresholds had been reached by the early twenty-first century. A scientific study of important planetary boundaries found that several of them had already been exceeded, including those for nitrogen, climate, and biodiversity[13] (See Figure 9.3).

Measuring the Relationship Between Economic and Ecological Systems

Ecological economists have developed different approaches to measuring the overall scale of human economic activity. One approach recognizes that both ecological and economic systems rely upon energy to support and expand the functions of life. Living systems obtain solar energy through plant photosynthesis. As the human economic system grows, a larger proportion of this **net primary product of photosynthesis (NPP)** is used directly or indirectly to support economic activity. This appropriation of photosynthetic energy takes place through agriculture, forestry, fisheries, and fuel use. In addition, human activities convert land from natural or agricultural functions for urban and industrial uses, transportation systems, and housing construction.

net primary product of photosynthesis (NPP) the biomass energy directly produced by photosynthesis.

carrying capacity the level of population and consumption that can be sustained by the available resource base.

According to recent studies, humans have appropriated about 25 percent of NPP, with much higher rates of 83 percent and 73 percent in cropland and major infrastructure (densely inhabited) areas. The rate doubled during the twentieth century, and is projected to increase further by 2050.[14] This gives another perspective on the "full-world" concept, implying that, particularly for agricultural and biomass production, there are significant planetary limits. These limits can be expressed in terms of **carrying capacity**: the level of population and consumption that can be sustained by the planetary resource base. We will discuss some specific implications of these limits, in areas such as water, agriculture, fisheries, and atmospheric systems, in future chapters.

Another approach for measuring the scale of human activity attempts to capture the multidimensional ways in which people impact the environment in a single index. The ecological footprint (EF) concept, originally developed by Wackernagel and Rees (1996), seeks to convert all human environmental impacts into a measure of the amount of land required to supply all the necessary resources and assimilate all the wastes. In other words, a person's ecological footprint is the amount of land required to support his or her lifestyle.

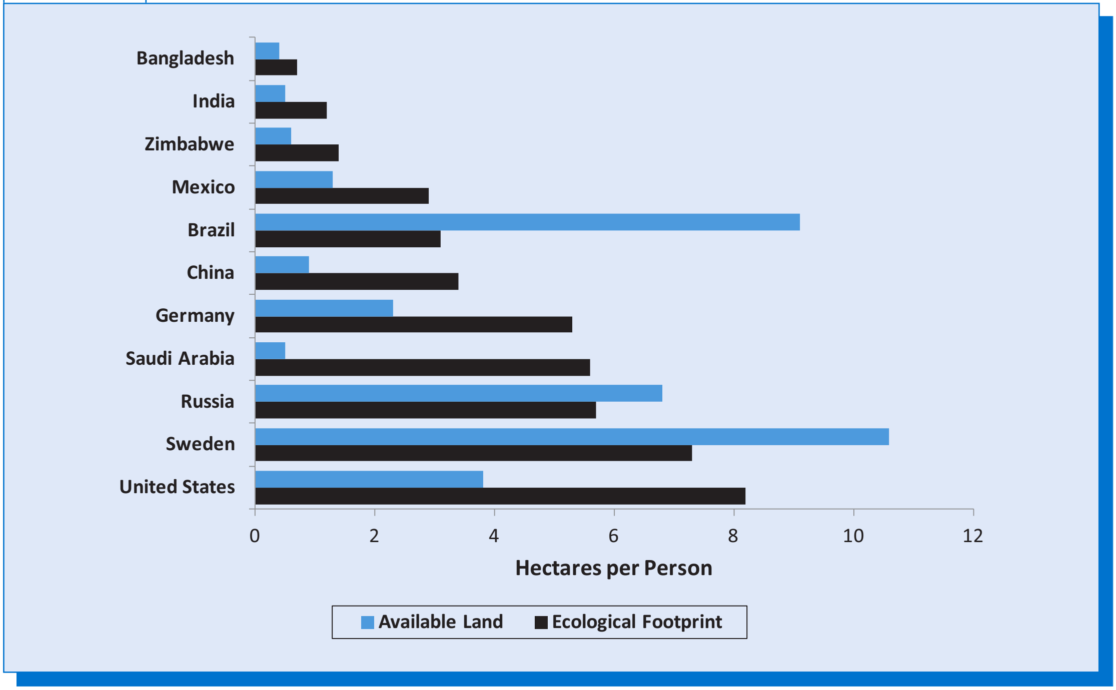
From a policy perspective, converting all environmental impacts into a single index may have some advantages, such as being able to determine whether overall impacts are increasing or decreasing. Measuring ecological footprints in land area units (hectares or acres) is relatively easy to understand and interpret. Also, the necessary data for the measurement of ecological footprints are readily available, on various scales from an individual to a country, and for most countries of the world, allowing for consistent measurement and comparisons.

Some effects convert easily to land-area footprints. For example, demand for meat converts to pasture area needed to raise livestock. Other impacts are more difficult to translate into land-area equivalents. For instance, carbon dioxide emissions from burning fossil fuels are accounted for in the EF approach based on the area of vegetation that would be required to absorb the carbon emitted. Calculation of a country's ecological footprint requires data on more than 100 factors, including demand for food products, timber, energy, industrial machinery, office supplies, and vehicles.

Comparing a region's ecological footprint to its available land helps determine whether the region's ecological impact is sustainable. Figure 9.4 presents the per-capita ecological footprints and available productive land for selected countries. The per-capita ecological footprints are much higher in developed countries than in developing countries. The average American requires about 8 hectares to support his or her lifestyle, while the average Indian requires less than one hectare.

Most countries, developed or developing, are currently running an ecological deficit. For example, we see in Figure 9.4 that the ecological footprint of the United States exceeds its available land by a factor of more than two. China's ecological footprint is nearly four times larger than its available land, and Saudi Arabia's footprint is 11 times greater than its land. The only countries in Figure 9.4 with an ecological footprint less than their available land are

Figure 9.4 Per-Capita Ecological Footprint and Available Land, Selected Countries, 2012



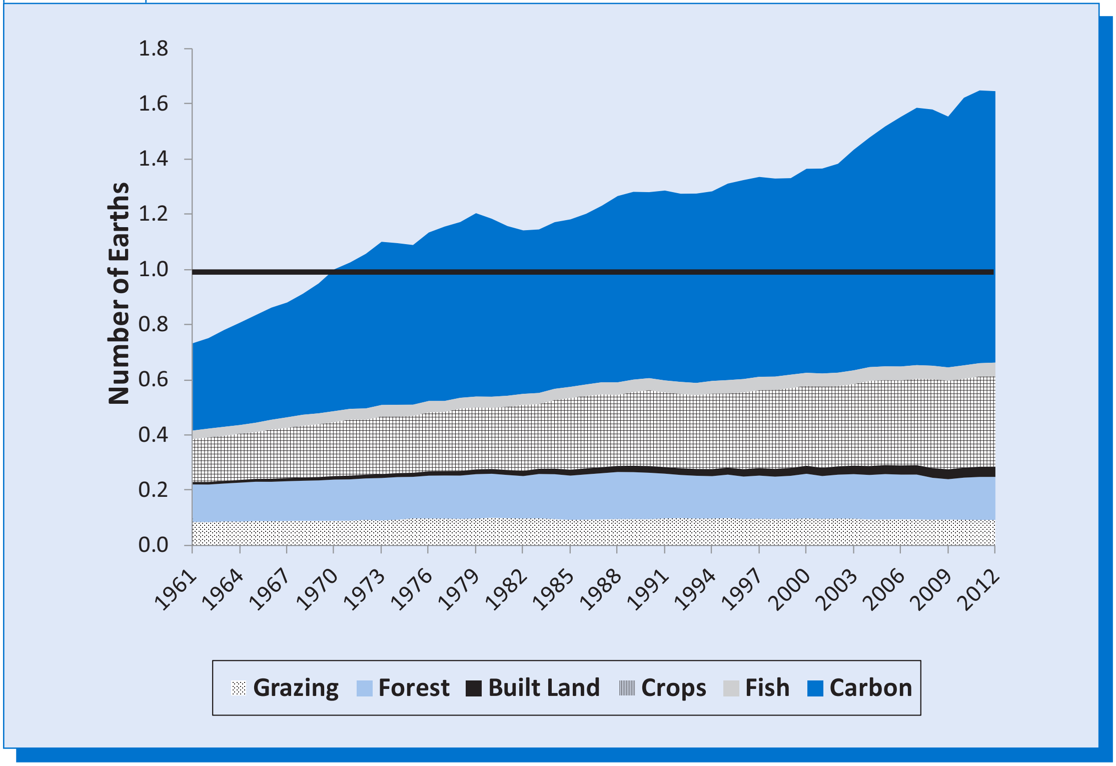
Source: Global Footprint Network, 2016.

Brazil, Russia, and Sweden. Note that this doesn't necessarily imply that these countries have pursued sustainable environmental policies. In the case of Russia in particular, per-person ecological impacts are relatively high but the total available land is even greater (Russia has more land area than any other country).

At the global level humanity's ecological footprint is 1.64 times greater than the available land on the planet. Thus the global ecological footprint, measured in terms of the number of earth-sized planets required to supply humanity's resources and assimilate its wastes, exceeds the one earth available to us, implying a long-term net depletion of natural capital. We see this in Figure 9.5, which breaks down humanity's ecological footprint into different types of impacts. About 60 percent of humanity's total ecological footprint is attributed to carbon emissions, and another 20 percent is related to the growing of crops.

The overall implication of Figure 9.5 is that humanity needs to reduce its ecological footprint in order to achieve sustainability. But the results also provide some guidance on policy efforts to achieve sustainability. Specifically, efforts to reduce carbon emissions, even while keeping other impacts constant, could be sufficient to reduce humanity's ecological footprint to less than one earth. Climate scientists estimate that in order to limit global warming to no more than 2°C we'll need to reduce global carbon emissions by 40–70 percent by 2050, and eventually to near zero by the end of the century (discussed in detail in Chapters 12 and 13).[15] A 70 percent reduction in carbon emissions, again while keeping other impacts constant, would reduce humanity's ecological footprint from 1.64 earths to 0.96 earths. Of course this doesn't imply that we should not direct effort toward reducing other ecological impacts, but it does indicate that we will not achieve a sustainable global footprint without significant reductions in carbon emissions.

Figure 9.5 Global Ecological Footprint, by Impact Type



Source: Global Footprint Network, 2016.

9.4 LONG-TERM SUSTAINABILITY

We have already mentioned sustainability in terms of natural capital. But how can this term be defined more precisely? We want to limit the loss or degradation of natural capital and to invest in its conservation and renewal. Taken in its strictest sense, this would mean that we could never use any depletable resource or conduct any economic activity that would substantially alter natural systems. In a world of more than 7 billion people, largely either industrialized or rapidly industrializing, this is clearly impossible. But unrestrained resource use and ever-increasing waste generation is also unacceptable. How can we strike the balance?

We have already examined elements of the standard economic answer to this question. The theories of external economies, resource allocation over time, and common-property and public goods management, which we outlined in Chapters 3–5, offer economic principles on when to use and when to conserve resources and on "optimal" pollution levels. In the long-term global context, however, these theories may be insufficient. Oriented toward individual markets, they may fail to guarantee environmental sustainability at the macroeconomic level. We need guidelines for overall conservation of the national and global resource bases. Within these guidelines, market solutions to specific resource and environmental management problems will become relevant.

strong sustainability the view that natural and human-made capital are generally not substitutable and, therefore, natural capital levels should be maintained.

We can distinguish between the concepts of **strong sustainability** and **weak sustainability**. (The use of the terms "strong" and "weak" in this context refers to how demanding our assumptions are and does not imply that one is necessarily better or worse than the other.) Strong sustainability is based on an assumption of very limited substitutability between natural and human-made capital. Weak sustainability assumes that natural and human-made capital are generally substitutable.[16]

weak sustainability the view that natural capital depletion is justified as long as it is compensated for with increases in human-made capital; assumes that human-made capital can substitute for most types of natural capital.

Taking the strong sustainability approach, we would keep separate accounts for human-made and natural capital and ensure that overall natural capital stocks were not depleted. It would be acceptable, for example, to cut down forests in one area only if similar forests were being expanded elsewhere so that the overall forest stock remained constant. Petroleum stocks could be depleted only if alternative energy sources of equal capacity were simultaneously developed. The implementation of strong sustainability would require extensive government intervention in markets and a radical change in the nature of economic activity.

Weak sustainability is easier to achieve. This principle allows for substitutability between natural and human-made capital, provided that the total value of capital is maintained. This may allow us, for example, to cut down forests in order to expand agriculture or industry. It does require, however, that there be an adequate accounting for the *value* of the cleared forest. The forest-clearing activity would not be acceptable unless the value generated in new human-made capital was greater than the value lost.

This principle is closer to standard economic theory. A private owner presumably would make such a calculation and would not willingly exchange a higher-valued resource for a lower-valued one. Government intervention would, however, be required to maintain even weak sustainability when:

- Private owners fail to consider the full ecological value of natural capital (say, a forest products company that considers timber values but is indifferent to endangered species).
- Property rights in natural resources are poorly defined, as is often true in developing countries. This can lead to the rapid plundering of a natural resource base by holders of short-term concessions or illegal users.
- Private property owners have short-term perspectives and fail to consider long-term effects such as cumulative soil erosion.
- Common property resources or public goods are involved.
- Truly irreplaceable resources are at issue, as in the case of species extinction or limited water supplies in arid areas.

Policy Choices and Discounting the Future

The choice between strong and weak sustainability may be difficult. In managing forest resources, for example, strong sustainability may be too restrictive, requiring a country to maintain the same area of forest cover under all circumstances. Weak sustainability, however, places no inherent limits on the amount of forest that can be cut, requiring only a sound economic accounting of its value. Although a middle ground must be defined, this cannot happen simply through the market process. It must be a conscious social choice.

One crucial factor in defining this middle ground is the issue of *discounting the future*. Our discussions of resource allocation over time (Chapter 5) and of cost-benefit analysis (Chapter 7) have highlighted the importance of the discount rate in market choices regarding resource use. In general, the higher the discount rate, the greater the incentive to exploit resources in the present. According to Hotelling's rule, private owners must expect a resource's net price to rise at a rate at least equal to the interest rate before they will conserve that resource for the future. This rarely occurs for most depletable natural resources.

Consider that at a 5 percent discount rate, net resource prices would be expected to double every fourteen years to induce conservation. Otherwise it is more profitable for the owner to extract the resource immediately and invest the proceeds at 5 percent. For renewable resources such as forests, the annual yield must be at least equal to the market rate of interest for private owners to practice sustainable management (see Chapter 19 for a full treatment of this issue). At lower yields, economic incentives favor clear-cutting the forest for immediate monetary gains. In effect, this means treating the renewable resource as a depletable resource and "mining" it out as fast as possible.

The logic of discounting imposes a stiff test on natural resource systems. Unless they can meet a certain yield level, immediate exploitation will take precedence over sustainable management. If major ecological systems and important natural resources fail this test, the resulting rush to exploit resources as fast as possible will make little provision for the future.

Here the strong sustainability principle becomes relevant: Can we trust that a world with much more human-made capital but a severely depleted resource base will meet the needs of the future? Or should we impose a stronger principle of resource conservation to guard our own and future generations' interests?

This is not just a philosophical debate about the long-term future. Many high-quality mineral resources could be largely used up within 30 to 40 years; tropical forests could be virtually eliminated in the same period; ocean and atmospheric systems could be severely degraded; water stored in aquifers could be exhausted and soil erosion could destroy the fertility of millions of acres of cropland within a generation. Applying a strict commercial discounting principle, all this destruction could be seen as quite "rational" and even "optimal."

Ecological economists have argued against using market-based discount rates to guide decisions on long-term resource use. They recommend using a sustainability criterion to promote **intergenerational equity**.[17] In this view, it is wrong to decide issues of long-term investment and conservation in the present simply by applying profit-maximizing criteria. This calls for social judgment regarding conservation of resources for the future.

intergenerational equity the distribution of resources, including human-made and natural capital, across human generations.

Complexity, Irreversibility, and the Precautionary Principle

Another major justification for a sustainability criterion relates to **ecological complexity** and **irreversibility**. Current ecological systems have evolved over many centuries to achieve a balance involving interactions among millions of species of plants and animals, as well as complex physical and chemical relationships in the atmosphere, oceans, and in freshwater and terrestrial ecosystems.

Extensive exploitation of natural resources permanently alters these ecological balances, with effects that are not fully predictable. In some cases, upsetting the ecological balance can lead to disastrous results—desertification, collapse of ocean food systems, depletion and pollution of aquifers, outbreaks of super-pests resistant to insecticides, and the like. Species extinction is a clear example of irreversible damage, imposing unknown economic and ecological costs in the future.

ecological complexity the presence of many different living and nonliving elements in an ecosystem, interacting in complex patterns; ecosystem complexity implies that the impacts of human actions on ecosystems may be unpredictable.

irreversibility the concept that some human impacts on the environment may cause damage that cannot be reversed, such as the extinction of species.

Ecological economists, therefore, argue for a **precautionary principle**—we should strive for minimum interference with the operation of natural systems, especially where we cannot predict long-term effects. This principle obviously defies easy definition in economic calculations of resource value and use. Such calculations, therefore, are of value only if we can place them in the broader ecological context, whose priorities must sometimes override market equilibrium logic.[18]

precautionary principle the view that policies should account for uncertainty by taking steps to avoid low-probability but catastrophic events.

first and second laws of thermodynamics physical laws stating that matter and energy cannot be destroyed, only transformed, and that all physical processes lead to a decrease in available energy (an increase in entropy).

entropy a measure of the unavailable energy in a system; according to the second law of thermodynamics entropy increases in all physical processes.

embodied energy the total energy required to produce a good or service, including both direct and indirect uses of energy.

9.5 ENERGY AND ENTROPY

As noted above, ecological economics places a special focus on energy. This implies looking to the laws of physics to understand fundamental drivers and limitations on ecosystems and economies. The **first law of thermodynamics** states that matter and energy can be neither created nor destroyed (although matter can be transmuted into energy through nuclear processes). This means that any physical process, including all economic processes, can be seen as a transformation of matter and energy from one form to another. The **second law of thermodynamics** tells us something more about the nature of this transformation. It states that in all physical processes energy is degraded from an *available* to an *unavailable* state.

The formal measure of this process is called **entropy**. Entropy is a measure of the *unavailable* energy in a system, so according to the second law entropy increases as natural processes proceed. The concept of entropy can also be applied to resources other than energy. An easily usable resource, for example a high-grade metal ore, has low entropy. A poorer grade of ore has higher entropy; it can also be used, but only through the application of energy from some other source to refine it.

The best way to understand this rather slippery entropy concept is to think in terms of a specific example, such as burning a lump of coal. In its original state, coal has low entropy—that is, it contains available energy. This energy can be obtained by burning the coal. Once burned, the coal is transformed into ashes and waste heat. The energy can now no longer be used, and the system has moved to a high entropy state.

Nicholas Georgescu-Roegen, a pioneer of ecological economic thought, argued that this law of entropy should be seen as the fundamental governing principle of economics.[19] All economic processes require energy, and transform energy from a usable to an unusable form. The physical outputs of any economic process, thus, can be said to contain **embodied energy**.

For example, an automobile embodies energy used to produce steel and to shape the steel into auto parts, as well as the energy used by workers to assemble it (or the energy used to run assembly-line robots). It also, of course, will require additional fuel energy to run. But eventually all this energy ends up in an unusable form. The fuel energy is dissipated in waste heat and pollution. The car is eventually scrapped and itself becomes waste. In the process, it has provided transportation services to its users, but the net result is the degradation of usable energy and resources into an unusable form.

If we think about the economic process from this perspective, two points become clear. One is that the economic process requires a continual stream of usable energy and resources (low entropy). The other is that it produces a continual stream of waste energy and other waste products (high entropy). Thus the input and output flows of resources and energy to and from the economic system become the fundamental governing mechanisms of production.

This perspective differs dramatically from standard economic theory, in which labor and capital inputs usually rank as the fundamental productive factors. Energy and resource inputs are often not specifically considered and sometimes omitted altogether. Energy and resource prices have no special significance over other input prices, and waste-flow effects, as we have seen, are generally defined as externalities rather than as a central reality of production.

The standard approach works well enough when energy and resources are abundant and cheap and when the environment easily absorbs waste and pollution damage. But as energy and resource demands grow, along with waste and pollution, the entropy perspective emerges as an important factor in understanding the relationship between the economic and ecological systems.

Energy Flows and the Economic Production System

Existing ecological systems are precisely organized for the efficient capture of energy. Millennia of evolution have developed complex and interdependent life systems that draw energy from the environment, using the **solar flux** (flow of sunlight). The fundamental process in all ecosystems is photosynthesis, by which green plants use the sun's energy to produce the organic compounds necessary for life. All animal life is completely dependent on plant photosynthesis, since animals lack the ability to utilize the solar flux directly.

solar flux the continual flow of solar energy to the earth.

Viewed from the perspective of the entropy law, the economic process is essentially an extension of the biological process of using low entropy to support life activity and, at the same time, increasing overall entropy. Industrial systems greatly increase the use rate of entropy. Low-entropy mineral deposits and stored low-entropy in the form of fossil fuels are mined to support the industrial process. Intensive agriculture also "mines" the stored resources of the soil. At the same time, the industrial system greatly increases the emission of high-entropy waste products into the environment.

In standard economic theory, as noted above, there are no inherent limits to growth. But the entropy theory implies that there are limits; economic systems must operate subject to the constraints of:

- Limited stocks of low-entropy resources, in particular high-grade ores and easily available fossil fuels;
- Limited capacity of soils and biological systems to capture solar energy to produce food and other biological resources;
- Limited capacity of the ecosystem to absorb high-entropy waste products.

In some cases, it may be possible to evade specific constraints. For example, we can increase the productivity of soils through adding artificial fertilizers. We cannot evade the entropy law, however, since fertilizer production itself requires energy. In effect, we can expand the limits of the agricultural system by "borrowing" low entropy from somewhere, but only with more rapid use of energy resources (and faster generation of waste and pollution). The one truly "free" source of low entropy is solar energy. Even in the case of solar energy, there are usually material and labor costs involved in capturing and using the available energy.

We can apply the entropy perspective to many different sectors of production: the energy sector itself, agriculture, mining, forestry, fishing, and other industrial sectors. This often gives a different picture of how these economic activities operate. A mining industry, for example, may show increasing productivity over time, measured in standard terms of output relative to labor or capital inputs. But if we concentrate on output per unit of energy inputs, we could well see declining productivity. In other words, we need increasing amounts of energy to achieve the same output as the quality of the mined ore declines.

In this case, we are substituting energy for labor and capital, an economically advantageous choice so long as energy is cheap. However, it means that our economic system becomes more dependent on fossil fuels, which, as we will see in Chapter 11, provide over 80 percent of our industrial energy. Pollution problems associated with fossil fuels also increase. To adapt to planetary entropy limits, we will need to shift to renewable sources of energy, based on the flow of solar energy—either solar power itself, or solar-driven sources such as wind energy.

Ecological economic analysis thus emphasizes the physical basis of production, as opposed to the economic costs of production. This provides a direct link to the physical realities of planetary ecosystems. If we focus only on economic costs, even though we attempt to internalize resource depletion and environmental costs, we may miss the full scope of resource and environmental impacts of economic activity.

9.6 ECOLOGICAL ECONOMICS AND POLICY

We have reviewed the general principles of ecological economics, offering a different and broader perspective on environmental issues. What are some implications of this perspective for economic policy? The ecological values that we have discussed are usually absent from standard market analyses. One way to link standard and ecological analysis at the microeconomic level is to use the concept of **ecosystem services** introduced in Chapter 6. Valuation of ecosystem services, while not necessarily reflecting all ecological functions, can provide a way to introduce these functions into economic markets—specifically, to set up systems that require users to pay for ecosystem services, creating an incentive to maintain and restore such services. At the macroeconomic level, an ecological perspective implies strong policies on climate, energy, biodiversity, water and oceans, and numerous other areas in which the human economy interacts with the environment.

> **ecosystem services** beneficial services provided freely by nature such as flood protection, water purification, and soil formation.

Payments for Ecosystem Services

Managers of natural resources typically face market incentives that provide financial rewards for exploitation. For example, owners of forest lands have a market incentive to cut down trees rather than manage the forest for carbon sequestration, wildlife habitat, flood protection, and other ecosystem services. These services provide the owner with no financial benefits, and thus are unlikely to sway management decisions. But the economic benefits provided by these services, based on their non-market values, may exceed the economic value of the timber. For example, a United Nations initiative has estimated that the economic benefits of ecosystem services provided by tropical forests, including climate regulation, water purification, and erosion prevention, are over three times greater per hectare than the market benefits.[20] Thus cutting down the trees is economically inefficient, and markets are not sending the correct "signal" to favor ecosystem services over extractive uses.

One solution to this inefficiency is to change market incentives so that preservation of ecosystems services becomes financially attractive to resource owners. This approach is known as **payments for ecosystem services (PES)**. PES systems provide incentives for resource owners to maintain or enhance ecosystem services. These incentives are normally monetary payments in exchange for the provision of various ecosystem services.

payments for ecosystem services (PES) the provision of economic incentives for resource owners to maintain or enhance ecosystem services.

In addition to encouraging the preservation of forest ecosystems, PES programs have been established that preserve watershed quality, biodiversity, and scenic beauty. For example, a joint PES project by The Nature Conservancy and the Ecuadorian government aims to protect the water supply to Quito (the capital of Ecuador) by paying land owners in the watershed to implement improved agricultural practices.[21] In a PES scheme in Bolivia to protect and improve water quality, small-scale farmers are encouraged to convert degraded agricultural land to other uses by free distribution of beehives and fruit trees.[22]

In order for a PES program to be successful at improving environmental quality, it should meet the following four criteria:[23]

conditionality a requirement of a successful PES program; the payments must be conditional upon a resource owner implementing changes that actually improve environmental outcomes.

additionality a requirement of a successful PES program; the environmental benefits must be in addition to what would have occurred without the payments.

leakage a requirement of a successful PES program is avoiding leakage; the environmentally-beneficial actions a resource owner takes must not be offset by other changes that are environmentally detrimental.

permanence a requirement of a successful PES program; the environmental benefits must persist for the long-term.

1. The payments must be conditional upon the resource owner implementing changes that actually improve environmental outcomes. This conditionality criterion requires that a system is in place to verify that the resource owner does what is agreed upon, such as planting trees or implementing sustainable agriculture practices.

2. The actions the resource owner agrees to take must display additionality. This means that the environmental benefits would not have been obtained without the payments. For example, suppose a landowner had no plans to cut down trees on his property. Paying this landowner to simply do what he already planned would not provide an additional environmental benefit.

3. The environmental benefits must not suffer from leakage. This means that the beneficial actions a resource owner takes are not offset by other changes. For example, suppose a landowner receives payments to preserve trees on a 20-hectare parcel that would have otherwise been cut for timber. In isolation, this would meet the additionality criterion. But if the landowner then decides to cut trees on another 20-hectare parcel that would otherwise not have been cut, leakage occurs and the payments produce no net environmental benefits.

4. Finally, a PES program must demonstrate permanence. This simply means that the environmental benefits should persist for the long-term. If landowners receive annual payments to preserve forest lands, but then cut down the trees once the payments stop (thus releasing their stored carbon into the atmosphere), the program produces no permanent benefits.

In addition to providing environmental benefits, PES programs are often advocated as a means to reduce poverty in developing countries. The expectation is that resource owners will only participate in voluntary PES programs if they increase their incomes, potentially lifting them out of poverty. But the linkages between PES programs and poverty are often more complex.[24] One problem is that the world's poorest people are often not owners of natural resources and are thus unable to receive payments in a PES program. Even when poor people do have secure ownership of land and natural resources, they may not own enough to make the PES programs worthwhile.

For example, in a PES program in Vietnam that provided payments on a per-hectare basis for forest preservation, the average small landowner only possessed two hectares. The PES payments were not sufficient to justify the transaction costs of applying for the program, and most of the payments went to larger, wealthier landowners.[25] Other barriers to participation may exist such as requirements that complex forms be completed, or that applicants file paperwork in distant locations.

There may also be negative indirect effects of PES programs on poor people. Low-income workers may lose their jobs if a PES program encourages conversion of agricultural land to protected areas. Subsistence hunter/gatherers may lose access to traditional areas as a result of PES programs. "There is reason to worry that the truly poor may find themselves unable to participate as suppliers of ecosystem services, displaced from their jobs, and cut off from natural resources that they previously exploited (either sustainably or otherwise)."[26] One illustration of an unexpected indirect effect was a PES program in Bolivia that successfully eliminated destructive logging. Once logging stopped the local roads were no longer maintained and small communities in the area were faced with higher transportation costs.[27]

PES programs have clearly produced significant environmental benefits in many cases—see Box 9.1 for one example. But to what extent PES programs have the potential to reduce poverty requires further study.

Box 9.1
PAYMENTS FOR ECOSYSTEM SERVICES IN UGANDA

A number of research studies in recent years have sought to document the quantitative environmental impact of PES programs. One such study, published in 2016, set up a randomized control trial (RCT) in Uganda to measure the impact of a PES program designed to reduce deforestation. (An RCT compares participants in a particular program with a similar group not in the program).

Farmers in the program received approximately US$30 per hectare per year for refraining from clearing forest lands. A total of 60 villages in western Uganda were randomly selected to participate in the PES program, while another 61 villages were selected to be the control group.

The researchers then used high-resolution satellite imagery to measure tree cover in the treatment and control villages. The results indicated that the PES program did reduce deforestation. Tree cover declined by 7–10 percent in the control villages, while it only decreased 2–5 percent in the treatment villages. The satellite data also revealed that leakage was not occurring by studying tree cover in forest lands around each village.

Only 32 percent of eligible participants in the treatment villages signed up for the PES program. Follow-up surveys determined that the low participation rate was attributed to insufficient marketing of the program and a concern among some landowners that the program was a scheme to take over their land. Of those who participated, 80 percent met the conditions of the PES contract. However, as the study only lasted two years the researchers suggested that deforestation rates could eventually return to baseline levels without further interventions.

Source: Jayachandra *et al.*, 2016.

Ecological Macroeconomics

An ecological perspective suggests that overall human impact on the planet is so great that it requires a fundamental change in economic systems to avoid an "overshoot-collapse" syndrome, as described in the basic limits-to-growth model discussed in Chapter 2. Some scientists and ecological economists have called for recognition of the current era as the "Anthropocene"—meaning a period in which human activities have become the dominant global force shaping Earth's climate and ecosystems.[28] In this period, an ecological economics approach suggests macro-level changes in:

- Energy systems, adopting renewable energy to prevent catastrophic climate change
- Agricultural systems, to promote long-term sustainability
- Population growth, which needs to stabilize to avoid ever-increasing human demands on the biosphere
- Nonrenewable resource use, to conserve resources for the future
- Renewable resources, to prevent over-use and preserve the integrity of water cycles, forests and fisheries, and conserve biodiversity

In each of these areas, standard economic analysis can provide some policy insights, but it will be important also to take a broader ecological perspective to understand the overall relationship between economic activities and the natural systems that support them. As we explore these topics in Chapters 10–20, we will draw on both standard and ecological perspectives as we seek to analyze each topic area and discuss policy perspectives.

Summary

Ecological economics takes a different approach from standard environmental economic analysis based on markets. It emphasizes the dependence of the human economy on natural ecosystems and gives special emphasis to the concept of natural capital. While much of standard economics is concerned with the accumulation and productivity of human-made capital, ecological economics focuses on the maintenance of the natural capital systems that support life and economic activity. Natural capital includes all the natural resources, oceans, atmosphere, and ecosystems of the planet. These must be accounted for and should be managed according to sustainable principles, so that their functions are not degraded over time.

In this perspective, economic systems cannot grow without limit but must achieve a sustainable scale for economic activity at which the planet's ecosystems are not subjected to undue stress. Significant evidence indicates that current economic activity exceeds these limits or badly strains them. One measure of this is the proportion of photosynthetic energy appropriated for human use, now about 25 percent of photosynthesis, with much higher proportions in agricultural and densely populated areas. Significant further growth in human demand would thus leave little room for other living systems of the earth.

The concept of sustainability, although important to managing natural capital, is difficult to define. A "weak" definition relies on the possibility of replacing natural ecosystem functions with human-made substitutes. A "strong" definition assumes that humans have limited ability to replace natural system functions and that a sustainable society must, therefore, maintain most of its natural systems without significant depletion or degradation.

Long-term sustainability involves issues of discounting the future and the question of our responsibility to provide for future generations. Economic incentives and property rights systems affect decisions regarding resource use, as does public policy on resource management. A precautionary principle is appropriate in cases in which irreversible effects may result from damage to complex ecosystems. Resource conservation for future generations requires social judgment in addition to economic calculation.

A special focus on energy in the economic system emphasizes the principle of entropy: available energy is limited, and its use governs all physical processes, including ecological and economic systems. This places a special importance on the use of solar energy and the limits of fossil-fuel energy. In general, an entropy analysis shows the limits of economic activity and the ecological price to be paid for exceeding these limits.

The principles of ecological and standard economics are both relevant to resource management issues. Sometimes the principles will conflict, but it is important to consider how best to apply both to specific resource and environmental issues, as well as to the measurement of economic output, human well-being, and ecosystem health.

Key Terms and Concepts

absortive capacity of the environment

capital depreciation

closed system

complementarity

decoupling

dematerialization

ecological complexity

ecological economics

embodied energy

empty-world economics

entropy

environmental degradation

first and second laws of thermodynamics

full-world economics

intergenerational equity

irreversibility

methodological pluralism

natural capital

natural capital depreciation

natural capital sustainability

net investment and disinvestment

net primary product of photosynthesis (NPP)

open system

optimal macroeconomic scale

physical accounting

precautionary principle

resource depletion

satellite accounts

scale limit

solar flux

steady state

strong and weak sustainability

substitutability

sustainable yield

throughput

Discussion Questions

1. In what respects is "natural capital" similar to human-made capital, and in what respects does it differ? We often speak of a "return to capital," meaning the stream of income generated by a capital investment. Can we speak of a return to natural capital? What are examples of investment in natural capital? Who is motivated to make such investments? Who would suffer if such investments were not made, or if "disinvestment" occurs due to resource depletion or environmental degradation?

2. Is the concept of optimal scale for an economy useful? If so, how would you go about determining it? Do you think that economies such as those in the United States, Europe, and Japan have reached optimal scale? Exceeded it? How about the economies of Latin America, Asia, and Africa? How would you relate the concept of optimal scale in the global economy to economic growth in national economies at different levels of development?

3. Distinguish the concepts of strong and weak sustainability, and give some practical examples, other than those cited in the text, for their application. Where is each concept most appropriate? Which economic policy measures are relevant to achieving sustainability?

Notes

1. Brown and Timmerman, 2015, p. 2.
2. Norgaard, 1989.
3. For a more detailed account of the development of ecological economics and its relation to economic theory, see Costanza *et al*., 2014; Krishnan *et al*., 1995; Martinez-Alier and Røpke, 2008.
4. See Ricardo, 1951 (original publication 1817).
5. See El Serafy, 2013, for a detailed analysis of ecological accounting.
6. For discussion of the implications of an ecological economics perspective for growth theory, see Daly, 1996; Harris and Goodwin, 2003; Farley and Malghan, 2016.
7. See Daly, 1996; Goodland *et al*., 1992; Goodland, 2016.
8. See Daly, 2007.
9. See Daly and Farley, 2011, chap. 7; Harris, 2016.
10. Goodland, 2016.
11. See Victor and Jackson, 2015, p. 238.
12. See for example Randers, 2012; Millennium Ecosystem Assessment, 2005.
13. Rockström *et al*., 2009.
14. Vitousek *et al*., 1986; Haberl *et al*., 2007; Krausmann *et al*., 2013.
15. See http://www.cop21.gouv.fr/en/why-2c/.
16. A discussion of the principles of strong and weak sustainability can be found in Daly, 2007; Martinez-Alier and Røpke, 2008, part VI A; Neumayer, 2003; Common and Stagl, 2005, pp. 377–379.
17. Norgaard and Howarth, 1991. See also Padilla, 2002; Page, 1997.
18. Application of the precautionary principle is discussed in Tickner and Geiser, 2004.
19. Georgescu-Roegen, 1993; see also discussion of Georgescu-Roegen and entropy in Martinez-Alier and Muradian, 2015, pp. 6–8.
20. Secretariat of the Convention on Biological Diversity, 2010.
21. http://www.watershedmarkets.org/casestudies/Ecuador_FONAG_E.html.
22. http://www.watershedmarkets.org/casestudies/Bolivia_Los_Negros_E.html.
23. Jindal and Kerr, 2007.

24. Grieg-Gran and Bishop, 2004.
25. To *et al*., 2012.
26. Ibid., p. 71.
27. Grieg-Gran and Bishop, 2004.
28. Monastersky, 2015; Brown and Timmerman, 2015; Dryzek *et al*., 2013, "Entering the Anthropocene," pp. 112–114.

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Web Sites

1. **www.ecoeco.org.** Web site for the International Society for Ecological Economics, "dedicated to advancing understanding of the relationships among ecological, social, and economic systems for the mutual well-being of nature and people." Their site includes links to research and educational opportunities in ecological economics.
2. **www.uvm.edu/giee/.** Web site for the Gund Institute for Ecological Economics at the University of Vermont, which "transcends traditional disciplinary boundaries in order to address the complex interrelationships between ecological and economic systems in a broad and comprehensive way." The Gund Institute sponsors the EcoValue project, which "provides an interactive decision support system for assessing and reporting the economic value of ecosystem goods and services in geographic context."
3. **www.sehn.org/ppfaqs.html.** Information provided by the Science and Environmental Health Network (SEHN), which promotes the precautionary principle as it relates to biotechnology and food engineering. Includes articles on definitions and applications of the precautionary principle.

CHAPTER

10

National Income and Environmental Accounting

Chapter 10 Focus Questions

- How do traditional national income accounting measures fail to account for the environment?
- How can traditional national accounting measures be adjusted to better reflect the importance of natural capital and environmental quality?
- What is the potential for alternative "green" measures of national welfare?

10.1 GREENING THE NATIONAL INCOME ACCOUNTS

Taking **natural capital** and environmental quality seriously affects the way that we evaluate measures of national income and well-being. Many economists would assert that the average person living in a country with a high per-capita national income is essentially "better off" than a person living in a country with a low per-capita national income. But the overall well-being of people is dependent on many factors other than income levels, including health, education levels, social cohesion, and political participation. Most important from the point of view of environmental analysis, a country's well-being is also a function of natural capital levels and environmental quality.

natural capital the available endowment of land and resources, including air, water, soil, forests, fisheries, minerals, and ecological life-support systems.

gross national product (GNP) the total market value of all final goods and services produced by citizens of a particular country in a year, regardless of where such production takes place.

gross domestic product (GDP) the total market value of all final goods and services produced within a national border in a year.

Standard measures of **gross national product (GNP)** or **gross domestic product (GDP)**[1] measure a country's level of marketed economic activity, which often implies how "developed" a country is. (See Appendix 10.1 for an introduction to national income accounting.) Macroeconomic analyses and international comparisons are commonly based on these measures, and they are widely recognized as important standards of economic progress.

Yet many analysts have pointed out that these measures can give a highly misleading impression of economic and human development. To be fair, GDP was never intended to be an accurate measure of a country's well-being. But politicians and economists often place disproportionate importance on GDP and act as if maximizing it is the primary objective of public policy. But maximizing GDP can conflict with other policy goals, such as promoting social equity or protecting the environment.

While GDP accurately reflects the monetary value of marketed goods and services, it fails to provide a broader measure of social welfare. Some of the common critiques of standard accounting measures such as GDP include:

- ***Volunteer work is not accounted for.*** Standard measures do not count the benefits of unpaid volunteer work, even though such work clearly contributes to social well-being, often consisting of the same activities as paid work (e.g., some teacher aides are paid while others are not).
- ***Household production is not included.*** While standard accounting measures include the paid labor from such market household activities as housekeeping and gardening, these services are not counted when they are unpaid.
- ***No consideration is made for changes in leisure time.*** A country's GDP rises if, *ceteris paribus*, total work hours increase.[2] However, no accounting is made for the loss of leisure time.
- ***Defensive expenditures are included.*** Recall from Chapter 6 that defensive expenditures that people incur to avoid environmental harms can be used to infer the value of some natural resources. Defensive expenditures also occur not just to avoid negative environmental impacts, but for many other reasons. One example is expenditures on police protection. If police expenditures are increased to counter a rise in crime levels, the increased spending raises GDP, but no consideration is made for the negative impacts of higher crime rates.

- ***The distribution of income is not considered.*** Two countries with the same GDP per capita may have significantly different income distributions and, consequently, different levels of overall well-being.
- ***Non-economic contributors to well-being are excluded.*** GDP does not consider the health of a country's citizens, education levels, political participation, or other social and political factors that may significantly affect well-being levels.

In our study of environmental issues, we must add another major criticism of standard accounting measures—they fail to account for environmental degradation and resource depletion. This issue can be important especially in developing countries, which depend heavily on natural resources. If a country cuts down its forests, depletes its soil fertility, and pollutes its water supplies, this surely makes the country poorer in some very real sense. But national income accounts merely record the market value of the timber, agricultural products, and industrial output as positive contributions to GDP. This may lead policy makers to view the country's development in an unrealistically rosy light—at least until the effects of the environmental damage become apparent, which in some cases may be decades.

If we are measuring social welfare with, so to speak, the wrong ruler, we may obtain policy prescriptions that could actually make a country worse off, rather than better off. Economic growth alone does not necessarily represent true economic development and may even lower human well-being if it is accompanied by growing inequity and environmental degradation. Attempts to define and estimate better measures of development has led to new proposals to adjust or replace traditional accounting measures in order to take into account resource and environmental factors. In this chapter, we discuss the estimation and application of several of these alternatives.

There have been numerous efforts to develop "greener" accounting measures. Interest in inclusion of the environment in national accounting began in the 1970s and 1980s, when several European countries began to estimate physical accounts for natural resources, such as forests, water, and land resources.[3] In 1993 the United Nations published a comprehensive handbook on environmental accounting, which was revised in 2003 and again in 2014.[4] The 2014 **System of Environmental-Economic Accounting (SEEA)** report describes three basic approaches to environmental accounting:

System of Environmental-Economic Accounting (SEEA) a framework developed by the United Nations and other international organizations to provide standards for incorporating natural capital and environmental quality into national accounting systems.

1. ***Measuring the physical flows of materials and energy.*** This approach looks at physical flows from the environment to the economy—the utilization of natural capital as inputs into production, such as cutting trees, harvesting fish, mining metal ores, or drilling for oil. It also looks at flows in the opposite direction, from the economy to the environment. This includes the disposal of solid wastes and emissions of air and water pollutants. Analysts construct tables that quantify physical flows into, or out of, different sectors of the economy, such as agriculture, mining, electricity generation, and manufacturing. For example, a table for air pollution might quantify the amount of different types of air pollutants, such as carbon dioxide, methane, nitrous oxides, and particulate matter, emitted by various sectors of the economy.
2. ***Measuring the stocks of environmental assets.*** The SEEA lists seven categories of environmental assets: mineral and energy resources, land, soil, timber, water, aquatic resources, and other biological resources. Environmental assets can be measured in both physical and monetary units. In principle, all environmental assets can be measured in physical units, such as tons of soil, acres of wetlands, or cubic meters of natural gas.

Valuation of environmental assets can be done by multiplying a physical quantity by a per-unit market price, or by using the non-market valuation techniques we discussed in Chapter 6. The 2014 report notes that current levels of economic activity are depleting and degrading these resources, leading to concerns about long-term availability.

3. ***The measurement of economic activity related to the environment.*** This approach tabulates environmentally-related monetary transactions, such as the amount of spending on environmental protection and resource management, the collection of environmental taxes, and the quantity of subsidies. It also includes the production of environmental goods and services, such as pollution-control equipment, the value of "environmentally-friendly" products, and spending on environmental technologies.

Note that these approaches are not necessarily mutually exclusive—we could theoretically implement all of them simultaneously. While many countries have adopted one or more of these accounts to some extent, no country has fully implemented the SEEA recommendations. Note that the SEEA framework seeks to integrate environmental accounting into existing methods of national accounting, typically using supplementary accounting tables. We will return to this topic later in the chapter, focusing on the measurement of physical flows and environmental assets (we won't discuss environmentally-related economic activity in this chapter, but will discuss some of these issues in Chapter 14).

Beyond the SEEA recommendations, other approaches seek to either adjust existing measures of national accounting, or devise entirely new national measures that provide a fundamentally different perspective on measuring national welfare. But before we delve into several specific measures, it is important to note that there is no universally accepted approach to environmental accounting. While various measures have been developed and implemented, there is no universally-accepted standard for environmental national accounting. We consider the future of environmental accounting at the end of the chapter.

10.2 GREEN GDP

Perhaps the most basic approach to environmental national accounting is to start with traditional measures and make adjustments that reflect environmental concerns. In current national income accounting, it is commonly recognized that some of each year's economic production is offset by the depreciation of manufactured, or fixed, capital, such as buildings and machinery.[5] In other words, while economic activity provides society with the benefits of new goods and services, each year the value of previously produced assets declines, and this loss of benefits should be accounted for. Thus standard national accounting methods produce estimates of **net domestic product (NDP)**, which starts with GDP and then deducts the annual depreciation value of existing fixed capital:

> **net domestic product (NDP)** gross domestic product minus the value of depreciation of produced, or human-made, capital.

$$NDP = GDP - D_m$$

where D_m is the depreciation of fixed capital. In 2015 the GDP of the United States was \$17.9 trillion. But the depreciation of fixed capital that year totaled \$2.8 trillion.[6] Thus the NDP of the United States in 2015 was about \$15.1 trillion.

Taking this logic a step further, we realize that each year the value of natural capital may also depreciate as a result of resource extraction or environmental degradation. In some cases, the value of natural capital could increase as well if environmental quality improves. The net annual change in the value of natural capital in a country can simply be added or subtracted from GDP or NDP to obtain what has been called **Green GDP**. So we would obtain Green GDP as:[7]

> **Green GDP** a national accounting measure that deducts a monetary value from GDP or NDP to account for natural capital depreciation and other environmental damages.
>
> **natural capital depreciation** a deduction in national accounting for loss of natural capital, such as a reduction in the supply of timber, wildlife habitat, or mineral resources, or environmental degradation such as pollution.

$$Green\ GDP = GDP\ (-\ D_m) - D_n$$

where D_n is the depreciation of natural capital. This measure requires estimating **natural capital depreciation** in monetary terms, rather than physical units such as biomass volume or habitat area. The methods discussed in Chapter 6 can theoretically be used to estimate such values, but obviously estimating all types of natural capital depreciation in monetary terms is a daunting task that would require many assumptions. Thus the estimates of Green GDP that have been produced focus on only a few categories of natural capital depreciation.

Attempts to estimate Green GDP date back to the 1980s. A pioneering 1989 analysis estimated the value of depreciation in Indonesia for three categories of natural capital: oil, forests, and soil.[8] The analysis found that accounting for natural capital depreciation could reduce GDP by 25 percent or more. A 2001 analysis in Sweden looked at a broader set of natural resource categories, including soil erosion, recreation values, metal ores, and water quality.[9] The results found that accounting for these factors would reduce GDP in Sweden by about 1–2 percent for 1993 and 1997. The author notes that while the overall adjustment may seem relatively minor, the analysis did not consider all potential environmental damages, such as climate change and loss of biodiversity. Also, looking at the effects of environmental degradation on the overall economy fails to recognize that some sectors are particularly affected, such as agriculture, forestry, and fisheries.

Another study estimated the value of changes in forest resources in India in 2003.[10] Based on timber and firewood market prices, the results indicated that while the overall physical stock of timber decreased, the value of timber resources actually increased due to higher prices. This illustrates the potential distortionary effect of looking at natural capital in monetary, rather than physical, terms. If we measure the value of natural capital at market prices, we can lose important information regarding the actual physical stock of those resources.

A significant effort to estimate Green GDP occurred in China in the early 2000s. In 2004 China's State Environmental Protection Agency (SEPA) announced that it would undertake a study to estimate the cost of various types of environmental damage. The initial findings released in 2006 indicated that environmental costs equaled about 3 percent of China's gross domestic product (GDP). The report was widely criticized because it failed to include numerous categories of environmental damage, such as groundwater contamination. Shortly afterward, Zhu Guangyao, the deputy chief of SEPA, released a separate report that concluded that environmental damage was closer to 10 percent of China's GDP—a value similar to what many observers were expecting. And in a 2007 report jointly produced by the World Bank and SEPA, the health and non-health costs of air and water pollution alone were estimated at 5.8 percent of China's GDP.[11]

The Green GDP report indicated that environmental damages in certain provinces of China were particularly high, implying that traditional GDP growth rates were being fully offset with environmental damages. This prompted some provincial leaders, who are largely evaluated based on provincial economic growth rates, to object to the entire project, and it was abandoned in 2007. But in 2015 China announced it was restarting its efforts with the implementation of "Green GDP 2.0," with pilot projects in certain regions.

The limited experience with attempts to estimate Green GDP reveals three important points:

1. ***Natural capital depreciation and environmental damages can amount to a significant portion of GDP.*** Green GDP can be significantly lower than GDP, by perhaps 10 percent or more in some countries.
2. ***Measuring the growth of GDP to illustrate changes in social welfare may not produce accurate results.*** Based on GDP growth alone, China is commonly touted as an economic development success story. But annual GDP growth in China appears to be largely or fully offset by environmental damages. Looking only at GDP to determine the trend in national welfare may lead policy makers to conclude that growth is robust. But accounting for environmental degradation suggests that much of China's recent apparent growth was at the expense of the environment, and this may be true for other countries also.
3. ***Monetization of natural capital needs to be approached carefully.*** As the example from India indicates, monetary estimates of natural capital, based on market prices, can fail to detect trends in physical stocks. As discussed in the SEEA, it is the physical stocks of natural resources that we are ultimately interested in measuring and tracking.

10.3 ADJUSTED NET SAVING

In addition to GDP, traditional national accounting methods also estimate saving and investment rates. These accounts provide some insight into how much a country is saving for its future. Starting with gross savings, including savings by governments, businesses, and individuals, **net domestic saving** is obtained after subtracting for fixed capital depreciation. Thus net domestic saving can be positive or negative. For example, from 2008 to 2011 net saving in the United States was negative, before turning positive in 2012.

We can propose that how a country manages its natural resources and environmental quality also provides information about whether it is saving for the future or causing depletion that may make future generations worse off. As in the calculation of Green GDP, we can adjust net domestic saving to incorporate a country's management of its natural resources. The World Bank has developed such a measure, called **adjusted net saving (ANS)**.[12] Unlike standard measures of national saving, ANS:

net domestic saving a national accounting measure equal to gross domestic saving less manufactured capital depreciation.

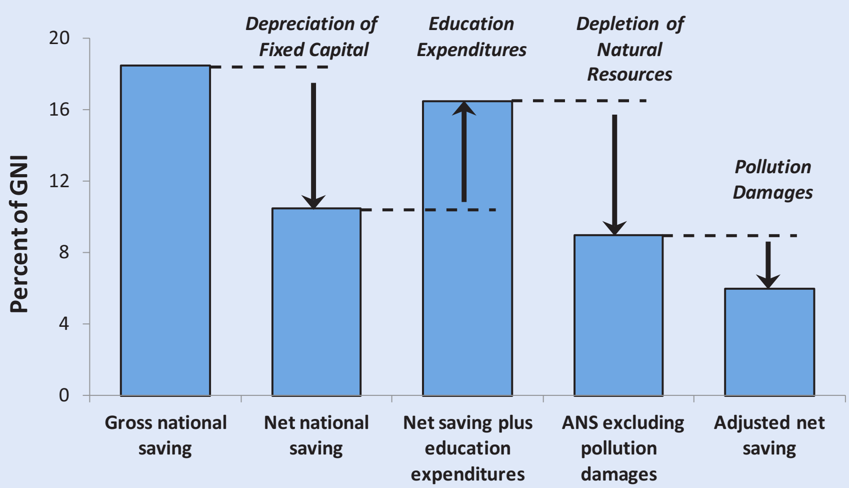
adjusted net saving (ANS) a national accounting measure developed by the World Bank which aims to measure how much a country is actually saving for its future.

> takes the broader view that natural and human capital are assets upon which the productivity and therefore the well-being of a nation rest. Since depletion of a non-renewable resource (or over-exploitation of a renewable one) decreases the value of that resource stock as an asset, such activity represents a *dis*investment in future productivity and well-being.[13]

An ANS analysis, particularly appropriate for developing countries, may show that what appears to be a development "success story" can conceal serious natural capital depletion and in some cases even a negative adjusted net saving rate.

ANS is normally calculated as a percentage of national income, although it could also be expressed in monetary units. The calculation of ANS is summarized in Figure 10.1. ANS is obtained using the following steps:

Figure 10.1 Calculation of Adjusted Net Saving



Source: World Bank, n.d.

Note: GNI = gross national income.

- ***Start with gross national saving.***
- ***Make a deduction to account for the depreciation of fixed capital to obtain net national saving.***
- ***Adjust for education expenditures.*** Unlike standard measures, ANS considers expenditures on education to be investments in the future of a society.[14] So expenditures on education are added to net national saving to reflect investment in human capital.
- ***Adjust for natural resources depletion.*** This adjustment considers three categories of natural resources: energy resources, minerals, and forests. For energy resources, a deduction is made for the depletion of nonrenewable fossil fuels—oil, coal, and natural gas. The deduction is calculated as the total market value of the resource minus its extraction cost. A deduction is made for the extraction of nonrenewable mineral resources, including copper, gold, lead, nickel, phosphate, and several other resources. The deduction is again calculated as the total market value of each mineral minus its extraction cost. Unsustainable depletion of a country's forest resources is considered a disinvestment in the future. As forests are renewable resources, it is possible that a country could actually increase its forest resources. Thus net forest depletion is calculated as the annual value of extraction for commercial uses such as timber and fuelwood, combined with an estimate of the net change in forest area.
- ***Adjust for pollution damages.*** Two pollutants are considered in this adjustment: carbon dioxide and particulate matter. Carbon dioxide emissions represent a disinvestment in a country's future as they contribute to damage from climate change. A country's annual emissions are multiplied by an assumed damage of $35 per ton of carbon.[15] Local air pollution damages from particulate matter are calculated based on lost future worker productivity due to death and illness.

The World Bank has calculated ANS rates for most countries of the world, with selected examples presented in Table 10.1. For most countries, the environmental adjustments are

Table 10.1 Adjusted Net Saving (ANS) Rates, Selected Countries, Percent of Gross National Income, 2014

Country	Gross National Saving	Fixed Capital Depreciation	Education Expenditure	Energy Depletion	Mineral Depletion	Net forest Depletion	Pollution Damage	ANS
Brazil	16.57	−11.83	5.54	−1.58	−0.64	−0.28	−0.43	7.34
China	49.45	−12.88	1.79	−1.30	−0.93	−0.08	−1.51	34.54
Congo, Dem. Rep.	11.42	−6.56	2.06	−1.20	−16.04	−14.59	−1.73	−26.64
Germany	26.34	−17.36	4.67	−0.04	0.00	NA	−0.35	13.26
Ghana	19.35	−5.04	5.84	−5.57	−4.55	−7.40	−1.03	1.61
India	31.65	−10.49	3.08	−1.02	−0.30	−1.62	−2.31	18.98
Kuwait	44.76	−6.29	3.19	−22.34	NA	0.00	−0.64	18.67
Mexico	20.09	−11.74	5.04	−4.36	−0.43	−0.21	−0.53	7.87
Philippines	38.23	−8.92	1.84	−0.18	−1.33	−0.21	−0.74	28.69
Russian Federation	24.31	−4.93	3.54	−8.82	−0.64	NA	−1.54	11.94
Uganda	19.54	−5.90	2.00	NA	−0.03	−11.50	−0.99	3.11
United States	18.02	−15.47	5.05	−0.64	−0.06	NA	0.48	6.42

Source: World Bank, World Development Indicators database.

Note: NA means data not available for this variable.

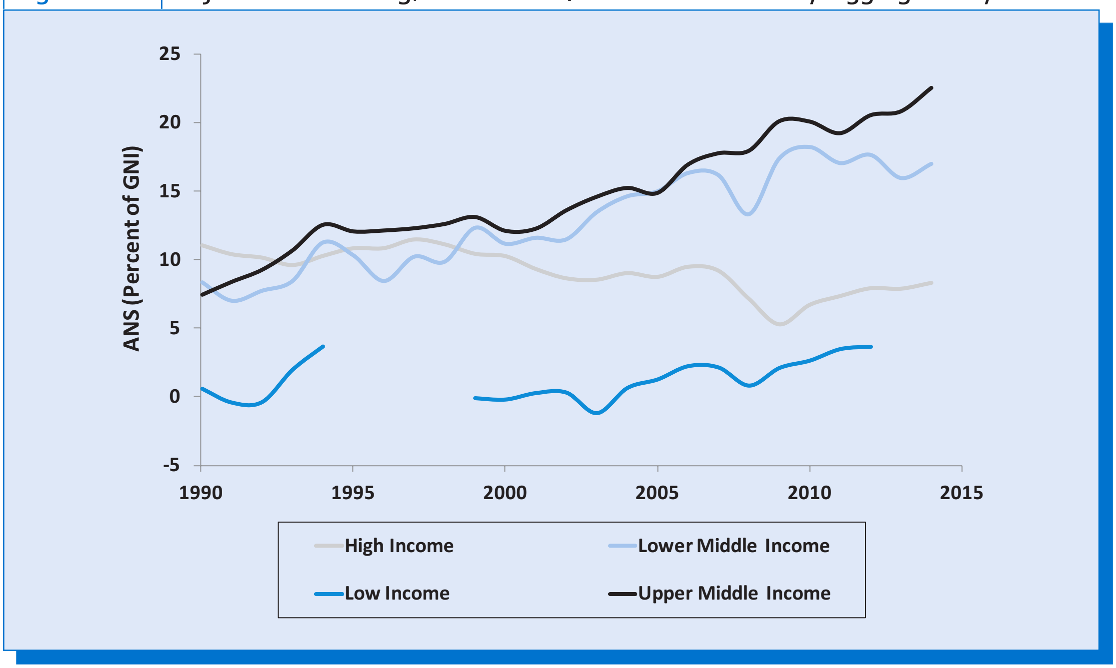
relatively minor. For example, the ANS rates of Germany and the United States are primarily a result of their respective net national saving rates and education expenditures. But the environmental adjustments can be quite significant in some countries.

The deduction for energy depletion is particularly high in Kuwait, and also significant in Russia, Ghana, and Mexico. High rates of both mineral and forest depletion lead to a negative ANS for the Democratic Republic of the Congo. Forest depletion is also significant in other African countries, such as Uganda and Ghana. The pollution adjustment tends to be a smaller share of national income, but is still high in such countries as India, China, and Russia.

We can see in Table 10.1 how relatively robust rates of gross saving can be misleading indicators. For example, both Mexico and Ghana start out with similar gross saving rates, but ANS for Ghana is near zero, while Mexico's ANS is around 8 percent. Kuwait and China also start out with similar gross saving rates, but Kuwait's ANS ends up being much lower due to its high depletion of energy resources. The Democratic Republic of the Congo is one of seven nations with negative ANS rates in 2014, including Afghanistan and Ukraine.

Note that the countries with the lowest ANS rates in Table 10.1 are poor African countries. The World Bank also tracks ANS rates over time for country groups based on income, as shown in Figure 10.2. We see that low income countries have consistently had the lowest ANS rates in the world, which may help explain why many low-income countries have failed to close the gap between them and the rest of the world. Between 1990 and 2000, ANS rates for middle- and high-income countries were similar. But since that time, ANS rates for lower–middle-income countries (including India) and upper–middle-income countries (including China) have increased, which provides insight into why middle-income countries have generally been catching up to richer countries in recent years.

Figure 10.2 Adjusted Net Saving, 1990–2014, World Bank Country Aggregates by Income



Source: World Bank, World Development indicators database.

Note: ANS rates for low-income countries not available for 1995–1998 and 2013–2014.

10.4 THE GENUINE PROGRESS INDICATOR

Green GDP and ANS adjust traditional national accounting measures to account for natural capital depreciation and environmental damage. But as with GDP, neither of these alternatives purport to measure social welfare. So another approach to greening the national accounts is to attempt to create a measure of social welfare basically starting from scratch. Perhaps the most ambitious attempt to date to design a replacement to GDP is the **genuine progress indicator (GPI)**.[16]

> **genuine progress indicator (GPI)** a national accounting measure that includes the monetary value of goods and services that contribute to well-being, such as volunteer work and higher education, and deducts impacts that detract from well-being, such as the loss of leisure time, pollution, and commuting.

One critique of GDP is that it includes all economic activity as a positive contribution to welfare. For example, all expenditures by the U.S. government Superfund for cleaning up toxic waste sites are contributions to GDP. The medical costs of treating diseases caused by air or water pollution are similarly added to GDP. If coastal homeowners or businesses whose property is damaged by an oil spill sue for damages, the legal expenditures involved as well as the cleanup costs also contribute to GDP. By this logic, the more pollution damage and resulting cleanup expense a country makes, the better off it is. Clearly this is irrational. Thus the GPI differentiates

> between economic activity that diminishes both natural and social capital and activity that enhances such capital. [The GPI is] designed to measure sustainable economic welfare rather than economic activity alone. In particular, if GPI is stable or increasing in a given year the implication is that stocks of natural and social capital on which all goods and services flows depend will be at least as great for the next generation while if GPI is falling it implies that the economic system is eroding those stocks and limiting the next generation's prospects.[17]

Like the previous measures discussed in this chapter, the GPI is measured in monetary units. The starting point of the GPI is personal consumption, based on the rationale that consumption directly contributes to current welfare.

In the United States, about 70 percent of GDP consists of personal consumption (the remainder is government consumption, investment, and net exports). The GPI then adds to personal consumption several goods and services that are considered to increase social welfare, some of which are not counted in GDP. The next step in calculating GPI is to deduct factors that are considered to decrease social welfare. Some of these deductions account for defensive expenditures—these are expenses associated with cleaning up pollution or attempting to repair or compensate for other environmental or social damage. In standard accounting, all such expenditures simply add to GDP.

The various steps in calculating the GPI, based on an analysis of the United States, are:[18]

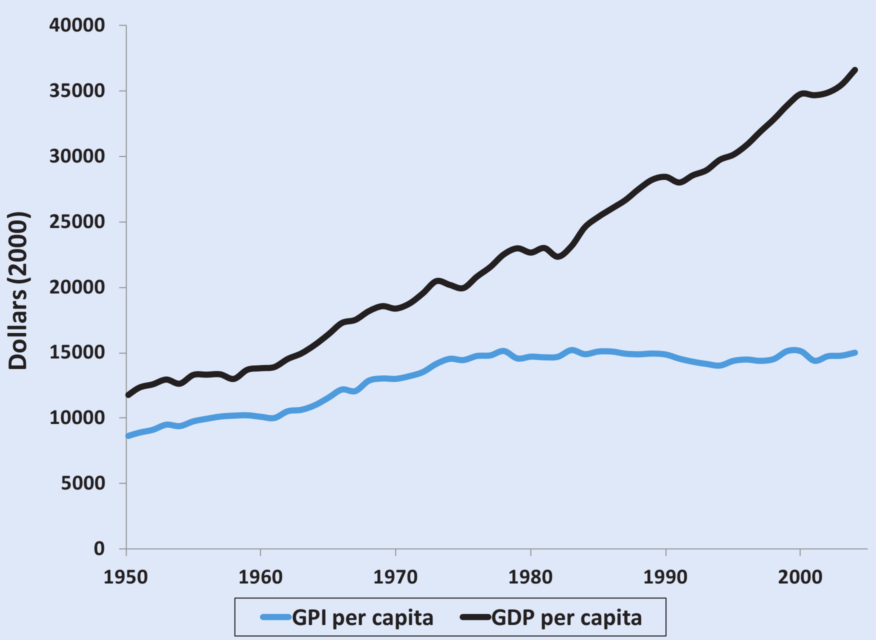
- ***Weighing consumption by income inequality.*** Personal consumption is adjusted to reflect the degree of income inequality in a society.
- ***Add in the value of household labor and parenting.*** GDP includes only paid household and parenting work, such as house-cleaning and daycare services. The GPI estimates the market value of unpaid household labor and parenting.
- ***Add in the value of higher education.*** This component of the GPI reflects the external benefit society receives from well-educated citizens—a positive externality estimated at $16,000 annually for each educated individual in the United States.

- ***Add in the value of volunteer work.*** GDP excludes the value of volunteer work, even though society clearly derives benefits from these services. The value of volunteer work hours is estimated using a market wage rate.
- ***Net benefits of consumer durables.*** This category is meant to capture the annual benefits consumers obtain from long-lasting goods, such as motor vehicles, appliances, and furniture. The annual expenditures on consumer durables are subtracted from these benefits to obtain the net benefits, which could be positive or negative.
- ***Net transportation benefits.*** The ability to use public highways and streets is assumed to provide consumers with direct benefits. But these benefits can be partially or fully offset by the time and cost of commuting, as well as deaths and injuries from auto accidents.
- ***Subtract the cost of crime.*** As crime detracts from social welfare, the GPI counts costs associated with crime as a deduction—unlike GDP, which would count these costs as positive additions. The cost of crime includes the costs of prisons and defensive expenditures such as buying locks and alarms.
- ***Subtract the loss of leisure time.*** GDP may increase simply because people work longer hours. However, the associated loss of leisure time is not considered in GDP. Based on estimates of total working hours, the GPI calculates the reduction of leisure time since 1969 (the year with the most leisure time in the U.S.).
- ***Subtract the cost of underemployment.*** Underemployed people include those who have become discouraged and given up looking for a job, people working part-time who would prefer a full-time job, and people who are willing but unable to work because of circumstances such as an inability to afford child care.
- ***Subtract the costs of pollution (air, water, and noise) and environmental defensive expenditures.*** Relying on studies using the valuation methodologies discussed in Chapter 6, the GPI estimates the economic damage from each type of pollution. Also, the cost of such products as air filters and water purification systems do not increase welfare but simply serve to compensate for existing pollution.
- ***Subtract the value of lost wetlands, farmlands, and forests.*** The GPI subtracts for losses of natural capital, including reductions in ecosystem services, lost recreation opportunities, and declining nonuse values.
- ***Subtract the costs of depleting nonrenewable energy sources.*** While GDP counts the market value of extracted nonrenewable energy sources as positive contributions, it fails to consider that a diminishing stock of resources imposes a cost on future generations. The GPI attempts to estimate this implied cost.
- ***Subtract the damages from carbon dioxide emissions and ozone depletion.*** As we discuss in Chapter 12, numerous economists have attempted to estimate the damage associated with carbon emissions. The GPI multiplies an estimate of the marginal damage from a ton of CO_2 by the cumulative tons emitted. Even though production of CFCs in the United States has been virtually phased out as a result of the 1987 Montreal Protocol, ozone damage continues as a result of past emissions.
- ***Adjust for net capital investment and foreign borrowing.*** Net investment (gross investment minus depreciation) is assumed to increase social welfare, while net depreciation or foreign borrowing is assumed to decrease social welfare.

As we might expect with all these adjustments, the GPI can differ significantly from GDP in magnitude and trends. A 2013 paper summarizes the estimates of GPI for 17 countries, focusing on how a country's GPI over time relates to its GDP.[19] For several developed countries, including Australia, Sweden, and the United States, GDP per capita and GPI per capita followed similar trends from the 1950s to the 1970s, after which GDP per capita continues to increase but GPI per capita levels off or decreases. This divergence is evident in Figure 10.3, showing data for the United States from 1950 to 2004. We see that GDP per capita steadily increased from 1950 to 2004. While GPI per capita grew along with GDP per capita until about the mid-1970s, since that time GPI per capita has remained relatively constant. This implies that gains in economic production have been approximately offset by negative factors such as the loss of leisure time, pollution, and the depletion of natural capital. Relying on the GPI in the U.S. for policy guidance, instead of GDP, would obviously present significantly different policy recommendations, focusing more on reducing environmental damages, preserving natural capital, and developing renewable energy resources.

Not all developed countries have followed the same pattern. For example, in the United Kingdom GDP per capita has increased rather steadily over time while GPI per capita peaked in the mid-1970s, significantly declined for about 15 years (largely a result of a reduction in social programs), and then began to rise even more rapidly than GDP per capita in the 1990s. And in Japan, GDP per capita and GPI per capita have increased almost in tandem, as a result of pollution reductions and a decreased reliance on domestic natural resources.

Figure 10.3 Comparison of GDP per Capita and GPI per Capita, United States, 1950–2004



Source: Talberth *et al.*, 2007.

Note: GPI = genuine progress indicator, GDP = gross domestic product.

The relationship between GDP and GPI in China has followed a pattern somewhat similar to that of the U.S. China's rapid economic development in the 1990s was matched by a comparable increase in GPI per capita. But since the late 1990s China's GDP per capita has continued to increase while its GPI per capita has leveled off. This can be attributed to a significant increase in external costs, rising economic inequality, and nonrenewable resource depletion. India has experienced a rapidly increasing GDP per capita, and GPI per capita has also steadily increased for all years with available data, although at a lower rate.

Combining the results from all 17 countries, the authors find that an increasing GDP per capita is strongly correlated with an increasing GPI per capita up to an income of about \$7,000 per person. However, further income gains are then correlated with a decreasing GPI per capita. Based on this result, the authors recommend a more equitable distribution of global resources, allowing poorer countries to develop economically and increase genuine progress. In developed nations they recommend reducing environmental costs and perhaps advocating welfare-enhancing reductions in GDP. They conclude that:

> If we hope to achieve a sustainable and desirable future, we need to rapidly shift our policy focus away from maximizing production and consumption (GDP) and towards improving genuine human well-being (GPI or something similar). This is a shift that will require far more attention to be paid to environmental protection, full employment, social equity, better product quality and durability, and greater resource use efficiency.[20]

Other GPI estimates also demonstrate divergences between GPI and GDP. A 2015 analysis of Brazil from 1970–2010 finds that GDP per capita increased by 137 percent over this period, while GPI per capita increased at a slightly lower rate of 100 percent.[21] The authors express concern that future economic growth in Brazil should be closely monitored to ensure that it does not lead to decreases in GPI. They recommend altering the nature of economic growth in the country, by focusing more on improving income distribution, reducing energy and material intensity in production, minimizing the environmental impacts of resource extraction, and maintaining the stocks of natural capital.

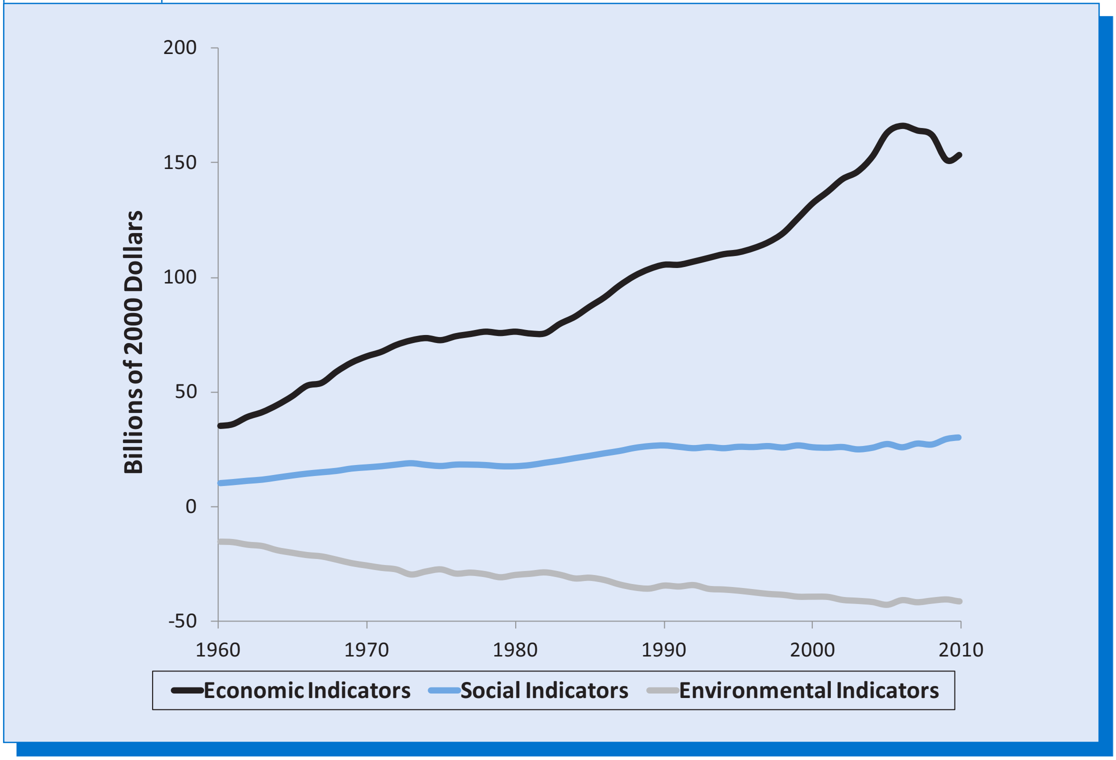
The GPI has also been estimated at the subnational level. For example, a 2009 analysis of the Auckland region in New Zealand showed that the GPI grew at nearly the same rate as the region's GDP during 1990–2006.[22] However, even in this case environmental losses grew at a faster rate than the GPI—rising 27 percent during this period while the GPI rose 18 percent. Thus the positive contributions to the GPI, in particular the growth of personal consumption, were enough to more than offset the higher environmental losses. So we need to recognize that a growing GPI can still occur despite increasing environmental damages.

This finding is further illustrated in Figure 10.4, which shows the economic, social, and environmental components of the GPI for the U.S. state of Maryland from 1960–2013. We see that while the economic contributions to the GPI rose steadily, the net social contributions increased only slightly and the environmental costs more than doubled.

This demonstrates a potential problem with any index that reduces all economic, social, and environmental factors into a single value. The overall index may fail to reflect important positive and negative trends that offset each other. Thus we should always refer to disaggregated results, such as the data in Figure 10.4, to achieve a more complete understanding of the changes occurring in a society and the potential policies that may be necessary to increase social welfare.

Like Green GDP and ANS, the GPI requires converting various environmental factors into a single metric—dollars. While this raises numerous methodological issues, as discussed in Chapter 6, we may also question whether disparate environmental resources and natural capital can be directly compared. Other approaches to measuring national well-being have

Figure 10.4 Components of the GPI for Maryland, 1960–2013



Source: Maryland Department of Natural Resources, http://dnr.maryland.gov/mdgpi/Pages/default.aspx.

been developed that avoid the use of a monetary metric but consider different aspects of the quality of life rather than using a dollar value. One recent approach, the Happy Planet Index, incorporates data on life expectancy, ecological impacts, and self-reported happiness (for more on the Happy Planet Index, see Box 10.1). We look at other recent indices attempting to measure the quality of life in the following section.

10.5 THE HUMAN DEVELOPMENT INDEX AND THE BETTER LIFE INDEX

While indices such as the GPI provide useful information and have been used by some policy makers, it currently seems unlikely that their adoption will become widespread around the world. More attention is paid to indices and measures published by international organizations such as the World Bank and United Nations. The most referenced quality-of-life index is probably the United Nations' **Human Development Index (HDI)**.

Human Development Index (HDI) a national accounting measure developed by the United Nations, based on three factors GDP levels, education, and life expectancy.

The HDI is calculated based on three components of well-being: life expectancy, education, and income. A report on the HDI is produced every year, with rankings and policy recommendations. In 2015 the countries with the highest HDI scores were, in order:

Box 10.1 THE HAPPY PLANET INDEX

The Happy Planet Index (HPI) is perhaps the most novel attempt to devise an entirely new approach to measuring national welfare in the context of environmental sustainability. The HPI, created by the British New Economics Foundation (NEF), asserts that the goal of society is to create long and happy lives for its members.[23] To do this, natural resources must be used and wastes generated. The HPI consists of three variables to reflect these concepts:

1. *Average life expectancy*: This measures whether a society's members lead long lives.
2. *Average subjective well-being*: This measures whether a society's members lead happy lives. The data are obtained from surveys that ask people how satisfied they are with their lives. Despite the simplicity of the approach, years of research have demonstrated that the results provide reasonably accurate estimates of an individual's welfare.
3. *Ecological footprint*: This measures a society's overall ecological impact (as discussed in Chapter 9). It is defined as the amount of land required to provide a society with the resources that it consumes and assimilate the waste that it generates. While it has been subject to methodological critiques, by converting all ecological impacts into a single value it provides an overall assessment of sustainability.

Average subjective well-being, measured on a scale between 0 and 1, is multiplied by life expectancy to obtain the "happy life years" of a society. Then the HPI is calculated as:

$$HPI = Happy\ Life\ Years / Ecological\ Footprint$$

The HPI has been calculated for 151 countries. The countries with the highest HPI scores are those whose citizens tend to be rather happy and long-lived but have a relatively modest ecological footprint, including Costa Rica, Vietnam, Belize, and Panama. One interesting aspect of the HPI is that a country's HPI ranking tends to be unrelated to its gross domestic product (GDP). The United States ranks 105th, only slightly better than Afghanistan (109th).

The interpretation and policy implications of the HPI are unclear. For example, India and Iraq have a higher HPI score than Germany or France. Does this imply that India and Iraq are more desirable to live in, or more ecologically sustainable, than Germany or France? Probably not. Another issue is whether a country's policies can affect happiness levels, which may be more a construction of inherent social and cultural factors rather than policy choices.

But despite its limitations, the HPI has received attention as an alternative or supplement to GDP, especially in Europe. A 2007 report to the European Parliament cites several strengths of the HPI, including:[24]

- It considers the ends of economic activity, namely, happiness and life expectancy
- The innovative way that it combines well-being and environmental factors
- Its calculations are easy to understand
- Data can be easily compared across countries

So while the HPI is unlikely to become a widespread alternative to GDP, it does provide information that is not currently captured in any other national accounting metric.

Norway, Australia, Switzerland, Denmark, the Netherlands, and Germany.[25] The HDI is highly, although not perfectly, correlated with GDP. For example, of the 30 countries with the highest HDI scores in 2015, all but two were also ranked in the top 40 by national income per capita. But there are some significant differences.

For example, Chile has about the same GDP per capita as Equatorial Guinea (around $21,000 each), and Sri Lanka has about the same GDP per capita as Namibia (around $10,000 each). But Chile has a much higher HDI score than Equatorial Guinea, and Sri Lanka has a much higher HDI score than Namibia. This is because both life expectancy and literacy measures in Chile and Sri Lanka are higher than in Equatorial Guinea and Namibia. So in some cases the HDI provides significantly more information than income alone.

Better Life Index (BLI) an index developed by the OECD to measure national welfare using 11 well-being dimensions.

A much more comprehensive attempt to assemble data on well-being in different nations is the Better Life Initiative launched in 2011 by the Organization for Economic Cooperation and Development (OECD).[26] Every two years the project has presented updated data on the **Better Life Index (BLI)**.[27] This indicator recognizes that well-being is a complex function of numerous variables. While material living conditions are important for well-being, so are quality of life and environmental sustainability. Further, the distribution of well-being across a society is important. The 2015 BLI report argues that

> a better understanding of people's well-being is central to developing better policies for better lives. Well-being is multidimensional, covering aspects of life ranging from civic engagement to housing, from household income to work-life balance, and from skills to health status. A thorough assessment of whether life is getting better requires a wide range of metrics, captured on a human scale, and able to reflect the diverse experiences of people.[28]

The BLI considers well-being a function of 11 dimensions:

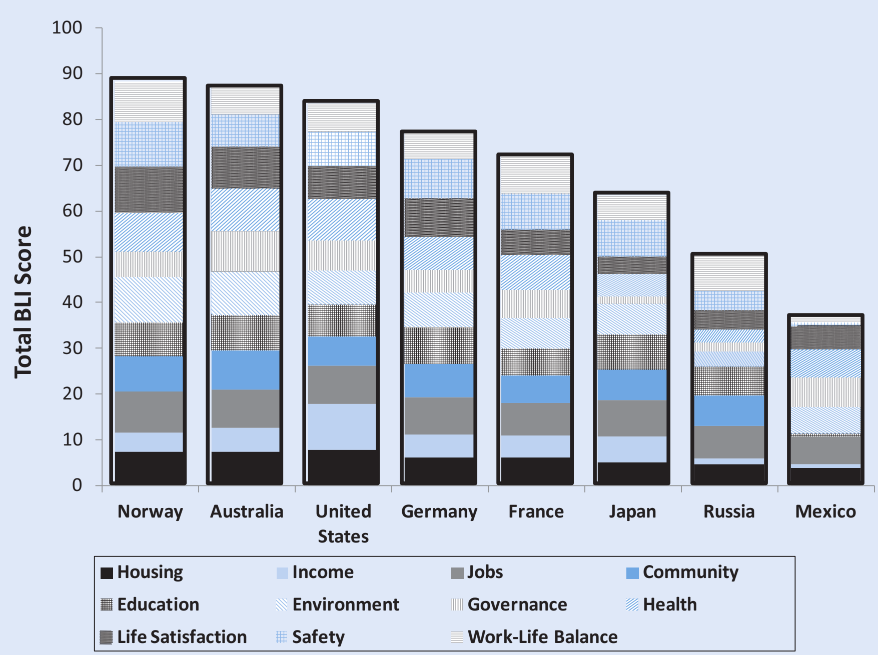
1. ***Income, Wealth, and Inequality***: The two main variables used for this dimension are disposable household income and net financial wealth. The BLI also considers the degree of inequality in income and wealth.
2. ***Jobs and Earnings***: This dimension includes data on unemployment, average earnings, and job security.
3. ***Housing Conditions***: This dimension considers the average number of rooms and characteristics of dwellings, as well as the percentage of income spent on housing.
4. ***Health Status***: The BLI includes life expectancy and a subjective evaluation of one's overall health status.
5. ***Work and Life Balance***: The BLI measures the proportion of employees working long (50 or more) hours per week, the time available for leisure and personal care, and the employment rate for women with school-age children.
6. ***Education and Skills***: This dimension includes the average years of education, the percentage of adults (25–64 years old) that have a secondary (i.e., high school) degree, and students' cognitive skills based on standardized tests.
7. ***Community***: This dimension is measured by people's responses to a standardized question asking whether they have friends or relatives that they can count on in times of need.
8. ***Civic Engagement and Governance***: This dimension is based on data on voter turnout and a composite index that measures citizen input in policy making.
9. ***Environmental Quality***: The two variables used for this dimension are particulate matter concentrations and people's subjective satisfaction with their water quality.
10. ***Safety***: This dimension focuses on threats to one's safety. It is measured using homicide rates and whether people say they feel safe walking alone at night.
11. ***Life Satisfaction***: This dimension measures people's overall satisfaction with their lives as well as reported positive and negative feelings.

The results are standardized across countries, resulting in a score from 0 to 10 for each dimension. While the BLI includes many components, it is designed to produce an overall well-being index. But how do we assign weight to the various components? One basic approach is to simply weigh each of the 11 dimensions equally. But it seems likely that some dimensions contribute to well-being more than others. The BLI report makes no specific recommendations on weighing the different dimensions. An interesting feature of the BLI is that a web site allows users to select their own weights for each of the dimensions. The OECD has collected input from over 100,000 users about their preferred weights for each dimension. Their results indicate that the highest rated dimensions vary considerably across countries. For example, the highest ranked dimensions are life satisfaction in the U.S., health in France, education in Mexico, work-life balance in Australia, safety in Japan, and income in Ukraine. Across all respondents, the top three dimensions are (in order): health, life satisfaction, and education. Environment is sixth, while income is ninth.

The BLI has been measured for the OECD member countries, as well as other countries, including Brazil, South Africa, and Russia, with plans to expand it to China, India, and Indonesia. Even for the OECD members, some results have to be estimated because of a lack of consistent data. Improving the standardization of data collection and reporting is one of the objectives of the Better Life Initiative.

Based on equal weighing of each dimension, Figure 10.5 shows how selected countries rank. Norway, Australia, and Denmark are the top three countries. The United States ranks ninth among OECD nations, performing well in terms of housing and income but ranking lower in terms of work-life balance and community. Realize that the equal weighing of each dimension reduces the importance of income levels relative to most other national accounting approaches, such as Green GDP and the GPI. As far as environmental rankings, the best performance is found in Norway, Australia, and Sweden while the lowest performances among the countries evaluated include South Korea, Russia, and Turkey.

Figure 10.5 Better Life Index Values for Selected Countries



Source: OECD Better Life Index web site, http://www.oecdbetterlifeindex.org/.

Box 10.2
BHUTAN'S GROSS NATIONAL HAPPINESS

Perhaps no country has advocated the need to devise alternatives to the gross national product (GNP) as much as the small Himalayan country of Bhutan. In 1972, King H.M. Jigme Singye Wangchuck introduced the concept of **gross national happiness (GNH)** to provide an alternative development philosophy to simply maximizing economic growth. He sought to achieve progress toward GNH by focusing on four policy objectives: equitable economic development, environmental preservation, cultural resilience, and good governance.[29]

While initially it was just a guiding concept, in recent years the Centre for Bhutan Studies (CBS) has sought to operationalize GNH.[30] The Centre has defined GNH as encompassing nine domains:

- Psychological well-being
- Standard of living
- Good governance
- Health
- Education
- Community vitality
- Cultural diversity and resilience
- Time use
- Ecological diversity and resilience

In 2015 the Centre conducted an extensive survey of over 7,000 Bhutanese households to assess the country's GNH.[31] Each domain was addressed by asking several questions. For example, for the ecological domain respondents were asked questions such as how concerned they were about air pollution, water pollution, waste disposal, flooding, and soil erosion. Based on "sufficiency" thresholds set by the CBS, the responses determine whether each household is sufficient in each of the nine domains. The results indicate that 43.4 percent of Bhutanese households have sufficiency in at least six domains and are thus considered either "deeply" or "extensively" happy. This is an improvement over an earlier survey in 2010, when 40.9 percent were similarly happy. Bhutanese have the most sufficiency in health and then in ecology and community vitality. Sufficiency is greater in urban areas, among the young, and among those with a formal education.

Bhutan, unlike most other countries, appears to not only be implementing an alternative to GDP but also using these results to guide future policies in a democratic manner.

Gross National Happiness seems to promote democracy in that it facilitates the process of citizens voicing their opinions on various dimensions of their lives to the Bhutanese government. The GNH survey and the index that the CBS constructs from it open a channel of communication between the government and society at large. People's voices on an array of domains reflected in the GNH index are the practical guiding forces for policy making in Bhutan.[32]

The BLI thus provides a comprehensive view of the many factors that influence well-being. Income is not presented as the starting point but as one component of many. BLI indicators can be used to design policies that improve well-being. One of the criteria used to choose the BLI variables is policy relevance. Several of the dimensions, such as education, housing, and environmental quality, can be directly improved with effective policies, although the linkage between other dimensions (such as subjective well-being) and policies needs further study. While the main focus of BLI is not on environmental and natural resource issues, its measures of environmental quality could be expanded or given greater weight in future.

BLI calculations also indicate data collection needs in various countries. The development of a consistent statistical agenda would improve the validity of the results across OECD countries and provide a basis for extending the results to other countries. At least one country, Bhutan, has created its own measure, **gross national happiness (GNH)**, which measures some of the same dimensions as BLI (see Box 10.2).

gross national happiness (GNH) the concept, originating in Bhutan, where a society and its policies should seek to improve the welfare of its citizens, as opposed to maximizing GDP.

10.6 ENVIRONMENTAL ASSET ACCOUNTS

An important issue to consider when evaluating any "green" national accounting approach is how its results can be used to assess the environmental sustainability of a society. As discussed in Chapter 9, we can define different levels of sustainability, which we identified as "weak" and "strong" sustainability. (Recall that these terms refer to different definitions, and do not imply that one is preferable to the other.) How well do the indicators introduced so far in this chapter reflect sustainability?

weak sustainability the view that natural capital depletion is justified as long as it is compensated for with increases in human-made capital; assumes that human-made capital can substitute for most types of natural capital.

strong sustainability the view that natural and human-made capital are generally not substitutable and, therefore, natural capital levels should be maintained.

Any index that monetizes various environmental factors and combines the results with traditional monetary aggregates, such as GDP, implicitly assumes a degree of substitutability among natural capital and economic production. For example, the GPI could remain constant if an increase in pollution damage is offset by an increase in personal consumption. Thus the GPI, along with other aggregate indices like Green GDP and ANS, can be considered appropriate metrics to address **weak sustainability** but not stronger forms of sustainability.[33]

If we are interested instead in achieving **strong sustainability**, we need to concern ourselves with the preservation of natural capital. A further distinction emphasized by some analysts is between "strong sustainability" and "very strong sustainability." Strong sustainability seeks to maintain the overall level of natural capital but allows the substitutability of different types of natural capital, at least for noncritical resources. For example, clear-cutting a forest could be appropriately offset by improving the ecological health or area of a wetland. Very strong sustainability seeks to maintain the levels of specific types of natural capital, allowing for substitutability only within each category of natural capital. Thus clear-cutting a forest could only be offset by creating a forest of similar extent and ecological value elsewhere.

environmental asset accounts or **(natural resource accounts)** national accounts that track the level of natural resources and environmental impacts in specific categories, maintained in either physical or monetary units.

critical natural capital elements of natural capital for which there are no good human-made substitutes, such as basic water supplies and breathable air.

The indicators discussed so far in this chapter are not necessarily designed to provide information on stronger forms of sustainability. Still, a few of them do provide some insight into strong sustainability objectives. The environmental components of the GPI, for instance, provide information on natural capital depletion, although not the overall level of natural capital.

An alternative approach is to maintain national accounts that track the levels of different types of natural capital. The UN's SEEA framework provides guidance on the maintenance of **environmental asset accounts** or (**natural resource accounts**), in both physical and monetary terms. These accounts are based on defining various natural capital categories, such as timber resources, mineral resources, agricultural land, and groundwater. The accounts may have different degrees of aggregation. For example, the account for mineral resources might include a separate account for each mineral or be disaggregated even further based on mineral quality, degree of accessibility, or location. The units would vary for different accounts based on the resource in question. So mineral accounts might be measured in tons, forest accounts in hectares of forest cover or board-feet of timber, groundwater accounts in acre-feet of water, and so on.

The two main strengths of environmental asset accounts in physical units are:

1. They provide a detailed picture of a country's natural capital levels and trends over time. A particular focus can be on ensuring that levels of critical natural capital are maintained.
2. They provide a means for assessing very strong sustainability. Since each category of natural capital is quantified in a separate account, policy makers can determine whether the levels of each are being maintained.

Environmental asset accounts can also be expressed in monetary units. In most cases, this simply involves multiplying a physical unit estimate by the market price per unit. For example, if a society has a standing timber stock of 500,000 board-feet of lumber and the market price is $5.00 per board-foot, then the asset value of their timber is $2.5 million. Environmental asset accounts in monetary terms offer the benefit of comparability, both among different types of natural capital and to traditional economic aggregates such as GDP. Unlike accounts in physical units, environmental asset accounts in monetary units can be used to give an overall measure of sustainability because gains and losses in different categories can be compared. Thus accounts in monetary units could be used to assess whether a society is achieving strong sustainability.

This is illustrated in Figure 10.6. For simplicity, assume there are only two natural resource assets in a society: timber and agricultural land. In Year 1 the society has a stock of 500,000 board-feet of timber and 6,000 hectares of agricultural land. At the market prices indicated in Figure 10.6, the total value of the environmental assets in the society is $8.5 million in Year 1. In the next year, the society harvests some of its timber stock but brings some additional land into agricultural production, as shown in the figure. If we kept asset accounts only in physical units (i.e., in this example, board-feet of timber and hectares of land), we would not be able to assess whether this society has maintained its overall level of natural capital (i.e., strong sustainability). But Figure 10.6 indicates that the monetary value of its natural assets has actually increased by $500,000, indicating that the overall value of natural capital is being sustained.

Comparing different assets in monetary units has both advantages and disadvantages. Suppose that the price of timber increased in Year 2 to $7.00 per board-foot. Even though the stock of timber was reduced by 100,000 board-feet, the value of the stock in Year 2 would be $2.8 million (400,000 board feet × $7.00). Even though the physical stock of timber was reduced, its market value increased relative to Year 1. So if we looked only at the monetary units, we could wrongly conclude that the society's stock of timber had increased due to factors such as increased planting or conservation. This again demonstrates that we need to be wary of the effect of changing prices on the value of a society's natural assets. This is particularly problematic for mineral and oil assets because the price of these commodities can fluctuate considerably.

Another problem with the monetary value approach is that the estimates in Figure 10.6 do not consider the loss of ecosystem services from harvesting timber. In addition to the loss of timber, there may have been a loss of wildlife habitat, erosion control, carbon storage, and other services. Ideally, assessing strong sustainability by aggregating various asset accounts should consider nonmarket benefits as well as market values. But estimating nonmarket values, such as ecosystem services and nonuse values, can be problematic, as discussed in Chapter 6. Thus any attempt to assess strong sustainability based on monetary values is likely to be incomplete or dependent on numerous controversial assumptions.

To assess "very strong" sustainability using Figure 10.6, we would need to look at the change in physical units over time. As this society's physical stock of forest resources is declining, we would conclude it is not achieving very strong sustainability for this resource.

Figure 10.6 Example of Environmental Asset Accounts

	Year 1		Year 2
Forest Resources		Decrease in Capital Stock	
Board-Feet of Timber	500,000		400,000
Price per Board-Foot	$5.00		$5.00
Timber Asset Value	$2,500,000		$2,000,000
Agricultural Land Resources		Increase in Capital Stock	
Hectares of Land	6,000		7,000
Price per Hectare	$1,000		$1,000
Agricultural Asset Value	$6,000,000		$7,000,000
Total Environmental Asset Value	$8,500,000		$9,000,000

Several countries have started to maintain environmental asset accounts. The United Kingdom's Office for National Statistics provides estimates for several environmental variables including energy consumption, air emissions, water use, waste generation, and environmental taxes.[34] Asset accounts for the following natural resources are also maintained:

- Oil and gas reserves—these accounts are maintained in both physical and monetary units.
- Timber asset account—this account includes the total physical stock of standing timber as well as its market value.
- Woodland ecosystem service account—this account estimates the nonmarket benefits of forest resources. The account is measured in physical units, including the tons of carbon storage, the tons of air pollution removed by trees, and the number of recreational visits. These are converted to monetary estimates, which indicate that trees provide 30 times the benefits in services left standing as opposed to harvested for timber.

Other countries that have prepared environmental asset accounts include Australia, Canada, Denmark, and Norway. Perhaps the most extensive system of environmental accounts, measured in physical units, is maintained by Sweden (see Box 10.3).

Box 10.3
ENVIRONMENTAL ACCOUNTS IN SWEDEN

In 2003 the Swedish government adopted sustainable development as an overall objective of government policy. In order to monitor progress toward sustainability objectives, an extensive database of environmental indicators is published on the Internet by Statistics Sweden (see "Web Sites" at the end of the chapter). The government recognizes that

> no generally accepted set of indicators for sustainable development has been worked up yet. . . . [But] Sweden is engaged in an ongoing effort to improve its environmental accounting, monitoring of environmental objectives, public health, green key ratios and index for development in the segregated districts of its metropolitan areas.[35]

Currently, categories of environmental indicators include:

- Material flow statistics
- Environmental goods and services
- Environmental impacts from households
- Environmentally related taxes and subsidies
- Emissions to air

Tracking trends over time have revealed some positive outcomes, along with the need for improvement in other areas. For example, Sweden's 2015 report indicates that domestic greenhouse gas emissions have steadily declined since the 1990s.[36] While this is obviously a positive trend, the report notes that:

> Emissions in Sweden are not the whole story. To see the total effect of Swedish final use, we have to look outside Sweden's borders as well as study what and how much we import, and what environmental impact production has in other countries. Both businesses and consumers in Sweden are buying more imported goods, which is a key reason why emissions are not increasing within Sweden's borders; they are happening somewhere else. Environmental impact is, however, increasing, in the countries where our goods are being produced.[37]

Thus, overall, total carbon emissions associated with Swedish consumption have actually stayed relatively constant since the 1990s. Other results in the report indicate that Swedish production of toxic chemicals has declined, that total material consumption has increased, and that Swedish waste generation per capita is above the European average.

10.7 THE FUTURE OF ALTERNATIVE INDICATORS

As we have seen in this chapter, numerous proposals have been made to address the deficiencies of traditional national accounting approaches in order to account for the environment or to better reflect social welfare, the ultimate goal of economic analysis. Most of these indicators provide some guidance on sustainability objectives as well. However, their implementation has been limited.

> The current state of environmental information around the world is, by most accounts, unacceptable. Environmental statistics are scattered among too many organizations. They are not coherent with one another, let alone with other types of statistics. They are incomplete and not consistent over time. This situation greatly restricts national and international capacity to develop and monitor progress toward environmental policy goals.[38]

While the SEEA provides guidance on various ways to approach environmental accounting, it indicates no particular preference for one approach over another. Instead it provides a menu of options from which a given country can choose to implement some but not others. We remain a long way away from a universally accepted approach to environmental accounting that is adopted by the majority of countries.

Recognizing the limitations of GDP and the need to develop indicators that incorporate social and environmental factors, in 2008 French president Nicolas Sarkozy created the Commission on the Measurement of Economic Performance and Social Progress. The commission was chaired by Nobel Prize–winning economist Joseph Stiglitz and the chair adviser was another Nobel laureate economist, Amartya Sen. Other members of the commission included numerous prominent economists. The goals of the commission were

> to identify the limits of GDP as an indicator of economic performance and social progress, including the problems with its measurement; to consider what additional information might be required for the production of more relevant indicators of social progress; to assess the feasibility of alternative measurement tools, and to discuss how to present the statistical information in an appropriate way.[39]

In September 2009 the commission produced a nearly 300-page report. The commission noted that policies promoting economic growth, as measured by GDP, may be unsuccessful in increasing well-being because they fail to account for other factors, such as environmental degradation

> traffic jams may increase GDP as a result of the increased use of gasoline, but obviously not the quality of life. Moreover, if citizens are concerned about the quality of air, and air pollution is increasing, then statistical measures which ignore air pollution will provide an inaccurate estimate of what is happening to citizens' well-being. Or a tendency to measure gradual change may be inadequate to capture risks of abrupt alterations in the environment such as climate change.[40]

The commission concluded that it is necessary to shift from an emphasis on measuring economic production to measuring well-being. It also distinguished between current well-being and sustainability. Whether current well-being can be sustained depends on the levels of capital (natural, physical, human, and social) passed on to future generations.

The commission hoped that its report would spur additional research on the topic of alternative indicators and encourage countries to investigate which indicators could provide the best information for measuring well-being and sustainability. Several countries have taken action.[41] In the UK, the Office of National Statistics was directed to conduct a survey asking people which indicators they thought should be used to measure well-being. In Germany a commission on "Growth, Prosperity, and Quality of Life" was established. Other countries attempting to reform national accounting include Canada, South Korea, Italy, and Australia. In the United States, the "State of the USA Project" has been funded by the National Academy of Sciences to develop a Key National Indicator System that

> will assemble the highest quality quantitative measures and related data, and will be presented on the Web in a simple and straightforward way so that interested people can assess whether progress is being made, where it is being made, by whom and compared to what.[42]

Another attempt to respond to the commission's recommendations has been the Better Life Index discussed previously. The 2011 OECD report on the Better Life Index notes that:

> The work of the Commission has been critical in giving impetus to our path-finding work on measuring progress and to a range of initiatives around the world aimed at developing better indicators of peoples' lives.[43]

The Commission's work was also an important motivation for the BRAINPOoL (Bringing Alternative Indicators into Policy) project funded by the European Union. BRAINPOoL evaluated a staggering 95 different "Beyond GDP" indicators that have been developed. Completed in 2014, the project recommended 18 indicators for further exploration, including several of the indicators we've discussed: the Better Life Index, the Genuine Progress Indicator, and Gross National Happiness. The project also identified several barriers to wider policy use of alternative indicators, including institutional resistance to change, the lack of a consensus around any single indicator, and the need for a compelling political narrative of the importance of non-GDP indicators.[44]

Absent a consensus regarding a single "best" alternative indicator, the research agenda appears focused on pursuing a range of indicators that are most relevant to measuring well-being and sustainability. Some environmental variables that current or future indicators should consider are rather obvious, such as measuring local air pollution levels and carbon emissions. But the measurement of a broader range of environmental impacts, such as biodiversity and ecosystem services, requires further research.[45] It also remains to be seen whether each country will rely on its own chosen set of indicators or whether a particular menu of indicators will become universally accepted. Another important objective is to develop consistent methods for measuring different variables, such as measuring carbon emissions and administering surveys to collect subjective data.

Improvement of data collection and international agreement on relevant indices may lead to better measures of "green" national income accounts and better ways to measure progress in terms of well-being and sustainability rather than simply marketed economic production. But measuring well-being and sustainability is only a first step toward designing and implementing polices to promote social and environmental progress. The chapters that follow examine the implications of environmental analysis and policy for a range of different areas, including energy, climate change, population, agriculture, fisheries, forests, and water.

Summary

Standard measures of national income such as gross domestic product (GDP) fail to capture important environmental and social factors. This can result in misleading measurements of national well-being that ignore important environmental problems and lead to misguided policy recommendations. A variety of approaches can be used to adjust existing national accounting measures or to provide alternatives.

Estimates of natural capital depreciation measure the depletion of natural resources such as oil, timber, minerals, and agricultural soils, in monetary units. Monetary estimates of these losses can be subtracted from the standard measures of national income and savings. An advantage of these measures is that they are compatible with existing national accounts. But a significant disadvantage is that they require all impacts to be converted to monetary values. Particularly for developing countries, results based on these approaches indicate a substantial impact of natural resource depletion and environmental degradation.

Various alternatives to GDP have attempted to incorporate environmental and social factors, including the Genuine Progress Indicator and Better Life Index. Results for the GPI suggest that a steadily increasing GDP is not necessarily correlated with increases in well-being, especially above moderate average income levels. Results for the BLI indicate that many other dimensions may be more important for well-being than income, such as health, education, and environmental quality.

Another approach is to maintain environmental asset accounts, tracking environmental indicators separately from GDP, either in monetary or physical units. Environmental asset accounts are particularly useful if one is interested in whether a society is achieving strong sustainability, focusing exclusively on natural capital.

Interest in alternative indicators has increased in recent years, exemplified by the Sarkozy Commission and the BRAINPOoL project. Still, no particular indicator, or even set of indicators, has yet to emerge as the preferred approach. A number of challenges remain, including developing consistent data collection methods and convincing politicians of the need for alternative indicators.

Key Terms and Concepts

adjusted net saving (ANS)

Better Life Index (BLI)

critical natural capital

environmental asset accounts

genuine progress indicator (GPI)

green GDP

gross domestic product (GDP)

Gross National Happiness (GNH)

gross national product (GNP)

Human Development Index (HDI)

natural capital

natural capital depreciation

natural resource accounts

net domestic product (NDP)

net domestic savings (NDS)

strong sustainability

System of Environmental and Economic Accounting (SEEA)

weak sustainability

Discussion Questions

1. What kinds of problems arise from the focus on standard GDP measures in discussing economic policy? How do these problems differ for highly industrialized countries like the United States and developing countries like Indonesia?
2. Of the various alternative indicators presented in this chapter, which one do you think is the most useful for policy guidance? Summarize the advantages of your preferred indicator.

3. What are some of the policy implications of using a revised measure that takes into account environmental and resource depreciation? How might the use of revised measures affect such policy areas as macroeconomic policy, trade policy, and resource pricing policy?

Exercise

1. Suppose you have been hired by the developing country of Equatoria to calculate its Green GDP. Assume for simplicity that only three adjustments need to be made to account for natural capital depreciation and pollution damages: timber capital, oil capital, and carbon dioxide damages. You have been given the following data:

Economic Data	
Gross domestic product:	$40 billion
Depreciation of manufactured capital:	$6 billion
Timber Data	
End-of-year timber stocks (board-feet):	2.0 billion
Start-of-year timber stocks (board-feet):	2.4 billion
End-of-year timber price ($/board-foot):	$6
Start-of-year timber price ($/board-foot):	$4
Oil Data	
End-of-year oil stocks (barrels):	500 million
Start-of-year oil stocks (barrels):	550 million
End-of-year oil price ($/barrel):	$60
Start-of-year oil price ($/barrel):	$50
Carbon Data	
CO_2 emissions (tons):	75 million
Damage per ton of CO_2 emissions:	$20

For timber and oil, you will need to calculate the value of depreciation, or appreciation, as the change in the total market value of the resource during the year, where total market value is the physical quantity times the resource price. What is the Green GDP for Equatoria, also accounting for the depreciation of manufactured capital? Would you recommend that Equatoria use Green GDP to measure its progress toward sustainability objectives, or perhaps some other indicator discussed in the chapter? Would you make any other recommendations to policy makers in Equatoria?

Notes

1. The difference between GNP and GDP concerns whether foreign earnings are included. GNP includes the earnings of a country's citizens and corporations regardless of where they are located in the world. GDP includes all earnings within a country's borders, even the earnings of foreign citizens and corporations. In the 1980s and 1990s most countries switched from relying primarily on GNP, to GDP. The rationale is that it is more meaningful to focus on economic activity within a country's borders.

2. *Ceteris paribus* is a Latin phrase meaning "other things equal," and is often used by economists to make clear what assumptions are used as the basis for analysis.
3. For a history of environmental accounting, see Hecht, 2007.
4. United Nations *et al.*, 2003; United Nations *et al.*, 2014.
5. Depreciation is simply a measure of the loss of capital value through wear and tear. For accounting purposes, it can be calculated using a "straight-line" formula according to which, for example, a new machine is estimated to lose 10 percent of its original value each year over a ten-year period, or using more complex valuation methods.
6. Estimates of fixed capital depreciation are obtained from tax records. Businesses are not taxed on the value of their fixed capital depreciation—thus they have a strong incentive to claim this deduction. Data on U.S. national accounts are available from the U.S. Bureau of Economic Analysis.
7. Note that Green GDP can be estimated using either GDP or NDP as the starting point.
8. Repetto *et al.*, 1989.
9. Skånberg, 2001.
10. Gundimeda *et al.*, 2007.
11. World Bank and SEPA, 2007.
12. Adjusted net savings is also called genuine savings.
13. Bolt *et al.*, 2002, p. 4.
14. Gross saving already includes fixed capital education expenditures, such as spending on buildings and buses. However, teacher salaries are not included, nor is spending on books and other educational supplies. ANS adds in these nonfixed capital expenditures.
15. Some analysts consider this a low value for carbon damages. We consider the economic damages from carbon emissions in Chapter 12.
16. An early version of the GPI was called the Index of Sustainable Economic Welfare (ISEW).
17. Talberth *et al.*, 2007, pp. 1–2.
18. Ibid. Note that various estimates of the GPI follow slightly different approaches, including adjustments specific to different countries.
19. Kubiszewski *et al.*, 2013.
20. Ibid., p. 67.
21. Andrade and Garcia, 2015.
22. McDonald *et al.*, 2009.
23. NEF, 2012.
24. Goossens, 2007.
25. United Nations, 2015.
26. The OECD is a group of the world's advanced industrial countries, now including some developing countries such as Mexico and Chile.
27. OECD, 2015.
28. Ibid., p. 17.
29. Braun, 2009.
30. CBS, 2011.
31. CBS, 2015.
32. Braun, 2009, p. 35.
33. Dietz and Neumayer, 2006.
34. Office for National Statistics, 2016.
35. Ministry of Sustainable Development, 2006, p. 69.
36. Statistics Sweden, 2015.
37. Ibid., p. 27.
38. Smith, 2007, p. 598.
39. Stiglitz *et al.*, 2009, p. 7.

40. Ibid., p. 8.
41. Press, 2011.
42. http://www.stateoftheusa.org/about/mission/.
43. OECD, 2011, p. 3.
44. BRAINPOol, 2014.
45. See, for example, Bartelmus, 2015.

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Web Sites

1. **http://ec.europa.eu/environment/beyond_gdp/index_en.html.** The web site for "Beyond GDP," an initiative to develop national indicators that incorporate environmental and social concerns. The project is sponsored by the European Union, the Club of Rome, the WWF, and the OECD.

2. **www.oecdbetterlifeindex.org.** The web site for the OECD's Better Life Index. Note that you can adjust the weights applied to each dimension to create your own version of the BLI.
3. **www.scb.se/en_/Finding-statistics/Statistics-by-subject-area/Environment/Environmental-accounts-and-sustainable-development/System-of-Environmental-and-Economic-Accounts/.** The web site for environmental accounts in Sweden.
4. www.brainpoolproject.eu/. Web site for the BRAINPOoL project, including an Excel spreadsheet with information on 95 different alternative indicators.

APPENDIX 10.1: BASIC NATIONAL INCOME ACCOUNTING

In this chapter we have discussed several modifications and alternatives to traditional national income accounting. Standard accounting measures, such as **gross national product (GNP)** and **gross domestic product (GDP)**, are widely accepted estimates of the health of a national economy. However, these measures have numerous technical and conceptual limitations. Some background knowledge of how they are calculated and interpreted is useful for understanding the arguments for adjusting or replacing these measures. If you have not taken an introductory macroeconomics course or need to refresh your knowledge, this appendix will help you work through the concepts presented in the chapter.

gross national product (GNP) the total market value of all final goods and services produced by citizens of a particular country in a year, regardless of where such production takes place.

gross domestic product (GDP) the total market value of all final goods and services produced within a national border in a year.

National income accounting was first developed in the United States in the 1930s to provide policy makers with information on the overall level of economic activity in the country. National income accounting was not designed to estimate the welfare of society—only the aggregate level of economic production. Also, at the time the accounts were being designed, environmental degradation was not an important issue.

For many years, the official measure of national economic activity in the United States was the gross national product, defined as the final market value of all new goods and services produced by the citizens of the country over a period of time (typically one year). GNP includes goods and services produced by U.S. citizens and corporations in foreign countries but not goods and services produced within U.S. borders by foreign citizens and corporations.

In the early 1990s the United States switched to gross domestic product as its official measure to conform with international standards developed by the United Nations. GDP measures the value of goods and services produced within the national boundaries of a country regardless of the producer's nationality. Thus GDP excludes production by U.S. citizens and corporations in foreign countries. In practice, there is normally little quantitative difference between GNP and GDP. In 2015 the values differed by less than 1 percent in the United States.

It is important to note that GNP and GDP measure only the final value of goods and services. Intermediate values are excluded to avoid double counting. For example, consider some of the steps involved in producing this textbook. First, a lumber company harvested wood and sold the wood to a paper mill. Then, the paper mill produced paper and sold it to a printing company. The printing company then printed the text under contract with the publisher. The publisher then sold the book to a retail store for final sale to you. If we add up the prices paid by the paper mill, printing company, publisher, retail store, and you, we end up with a value much higher than the price you paid for the book. The greater the number of intermediate production steps taken to produce an item, the higher the sum of all the prices paid. So all the intermediate steps are not counted, and only the final price you paid is included in GNP and GDP.

Since it may be difficult in practice to distinguish intermediate from final goods, the accounting method generally used to compute GNP/GDP is the **value-added method**, in which the extra value added at each step of the production process is counted. In the textbook example, the value added for the paper mill is the value of its output minus the cost of inputs purchased from the lumber company. The sum of the values added at all stages of production is equal to the value of the final good.

> **value-added method** the additional value of a good or service from each step in the production process.

GNP and GDP only count the production of new goods. If you purchased this book secondhand from a store or other student, then it would not be included in the national account. The sale of used products does not contribute to current economic production.

Adjusting for Depreciation, Population Growth, and Inflation

One reason GDP is not the best measure of national income is that a portion of investment in capital equipment, such as factories and machinery, simply replaces worn-out capital. Since capital that wears out or becomes obsolete decreases national wealth, the depreciation of this capital should be counted as a deduction from GDP. Gross investment minus depreciation is called net investment. If we deduct capital depreciation from GDP we get a measure called **net domestic product (NDP)**. The depreciation of fixed capital amounts to about 10–15 percent of GDP in the United States.

Of course, politicians and economists hope that the economy expands over time and GDP increases. But an increase in GDP does not necessarily indicate greater wealth for a country's citizens. GDP could increase simply because the country has a higher population. We can account for population growth (or decline) in national accounting by calculating GDP per capita, equal to GDP divided by population. Data on GDP per capita also allows us to compare economic production across different countries. For example, U.S. GDP is much greater than Swedish GDP, but when we adjust for population size we find that GDP per capita is higher in Sweden than in the United States.

> **net domestic product (NDP)** gross domestic product minus the value of depreciation of produced, or human-made, capital.
>
> **constant dollars** an adjustment of economic time series data to account for changes in inflation.
>
> **real GDP** gross domestic product corrected for inflation using a price index.

The other factor we need to control for when comparing GDP values across time is inflation. Remember that GDP is based on market prices and it could grow simply because market prices have risen. So when comparing GDP data from different years, we need to use **constant dollars**. For example, suppose that the general level of prices in 2017 was twice as high as it was in 1990. So if we wanted to compare GDP for these two years, we could compare them using 2017 dollars by doubling the GDP from 1990. Or we could compare them using 1990 dollars by dividing the GDP for 2017 in half. The first method gives us **real GDP** in 2017 dollars, while the second gives us real GDP in 1990 dollars.

U.S. GDP has grown tremendously in recent decades. As seen in Table A10.1, GDP increased by a factor of 51 between 1950 and 2015 if we do not consider any adjustments. Adjusting for population, we find that economic production per person has increased by about a factor of 25. But most of this increase is due to inflation. When we adjust for differences in price level by calculating real GDP per capita in 2015 dollars, we discover that economic production per person has actually increased by a factor of 3.2. This still suggests a large increase in the standard of living for the average American, but a much less significant increase than would be implied looking at the unadjusted aggregate GDP data.

Table A10.1 Historical Gross Domestic Product (GDP) Data, United States

Year	Unadjusted U.S. GDP ($ Billion)	Unadjusted GDP per Capita (Dollars)	GDP per Capita in 2015 Dollars
1950	300	1,971	15,745
1960	543	3,007	18,847
1970	1,076	5,247	25,224
1980	2,863	12,598	31,093
1990	5,980	23,970	39,369
2000	10,285	36,450	48,865
2010	14,964	48,374	52,462
2015	17,947	55,837	55,837

Sources: U.S. Bureau of Economic Analysis and U.S. Census Bureau web sites.

Note: Real GDP calculated based on adjustment using the BEA's price indices for GDP.

Comparing GDP for Different Countries

A final adjustment that is made when comparing GDP data across countries is to adjust for **purchasing power parity (PPP)**. Even if we use currency exchange rates to put all countries' GDP per capita in U.S. dollars, we should still adjust for differences in what a dollar can purchase in different countries. For example, a U.S. dollar converted into Chinese currency will buy a lot more in China than it will in the United States. As mentioned above, Sweden has a higher GDP per capita than the United States, but when we adjust for PPP, GDP per capita is higher in the United States than in Sweden because of the relatively high prices in Sweden.

purchasing power parity (PPP) an adjustment to GDP to account for differences in spending power across countries.

National income accounting data illustrate the varying economic conditions of people in different countries. We can use the data to compare rates of economic development and to determine income inequality between countries. But we need to be careful about interpreting national accounting data. GDP measures only the aggregate level of economic production; it does not measure social welfare. If GDP per capita rises only because people are working longer hours, we cannot conclude that they are happier. Also, GDP per capita could increase only because the wealthy members of society are becoming wealthier. GDP data tell us nothing about the level of economic inequality in a country. This and other known problems with GDP make it important to be aware of its limits as a measure of well-being—even before we consider the environmental and resource issues discussed in this chapter.

Key Terms and Concepts for Appendix 10.1

- constant dollars
- gross domestic product (GDP)
- gross national product (GNP)
- net domestic product (NDP)
- purchasing power parity (PPP)
- real GDP
- value-added method

PART

IV

Energy, Climate Change, and Greening the Economy

CHAPTER

11

Energy: The Great Transition

Chapter 11 Focus Questions

- What is the special role of energy in economic systems?
- What are current and future demands for energy?
- Is there a danger of energy shortages?
- Can we shift from fossil fuel-based energy to renewable energy systems?

11.1 ENERGY AND ECONOMIC SYSTEMS

Energy is fundamental to economic systems and, indeed, to all life. On deep ocean floors, far below the reach of sunlight, giant tubeworms and other strange life forms cluster around heat vents. Energy from the earth's interior drives their metabolic processes. On the earth's surface and at shallower ocean levels, all plant life depends on sunlight, and all animal life is dependent directly or indirectly on plants. (The few plants that can live without direct sunlight make use of nutrients in the soil deposited by the decay of other plants.) Our own equally critical need for energy is partially camouflaged in a modern economy. Measured in terms of gross domestic product (GDP), energy resources represent only about 8 to 10 percent of economic output,[1] but the other 90+ percent is absolutely dependent on energy inputs.

In less developed, agrarian economies, the dependence is more evident. People's basic need for food calories is, of course, a need for energy input. Traditional agriculture is essentially a method of capturing **solar energy** for human use. Solar energy stored in firewood meets other basic needs for home heating and cooking. As economies develop and become more complex, energy needs increase greatly. Historically, as supplies of firewood and other **biomass** proved insufficient to support growing economies, people turned to **hydropower** (also a form of stored solar energy), then to coal, and then to oil and natural gas as major energy sources. In the 1950s nuclear power was introduced into the energy mix.

Each stage of economic development has been accompanied by a characteristic **energy transition** from one major fuel source to another. Today, fossil fuels—coal, oil, and natural gas—are by far the dominant energy source in industrial economies. In the twenty-first century, the next great transition in energy sources has started—from nonrenewable fossil fuels to renewable energy sources. This transition is being motivated by many factors, including concerns about environmental impacts (particularly climate change), limits on fossil fuel supplies, and prices.

> **solar energy** the energy supplied continually by the sun, including direct solar energy as well as indirect forms such as wind energy and flowing water.
>
> **biomass** an energy supply from wood, plant, and animal waste.
>
> **hydropower** the generation of electricity from the energy in flowing water.
>
> **energy transition** an overall shift of energy consumption away from fossil fuels toward renewable energy sources.

Government policies will have significant influence on the nature and speed of this transition. Current energy markets bear little resemblance to the efficient unregulated markets described in Adam Smith's *Wealth of Nations*. Instead, energy markets are heavily subsidized and regulated. In particular, fossil-fuel subsidies by governments around the world total about \$500 billion per year, while subsidies for renewable energy are about \$120 billion.[2] (For more on energy subsidies, see Box 11.1.)

Energy prices also generally fail to reflect the costs of negative externalities. As we saw in Chapter 3, economic theory suggests that a commodity be taxed according to its externality damages. In the case of energy markets, externalities are rarely fully internalized. Removing distortionary subsidies and instituting appropriate externality taxes could significantly speed the transition from fossil fuels to renewable energy sources.

While getting the prices of different energy sources "right" is critically important, we should also note a different, more ecologically oriented, perspective on energy. Theorists of the ecological economics school see energy as fundamental to economic development and focus on a crucial distinction between the **nonrenewable stock** of fossil-fuel reserves and the **renewable flow** of solar energy.[3] In this perspective, the period of intensive

> **nonrenewable stock** See "nonrenewable resources."
>
> **renewable flow** the continuous quantity of a renewable energy source supplied over time, such as the quantity of solar energy available each year.

Box 11.1
FOSSIL FUEL SUBSIDIES

The International Energy Agency estimates that governments spent about $500 billion in 2015 to subsidize fossil fuels. According to the International Institute for Sustainable Development (IISD), global subsidies to fossil fuels may be larger, on the order of US$600 billion per year, but since there is no international framework for regularly monitoring fossil-fuel subsidies the precise figure is unknown. It is certainly much larger than total subsidies for renewable energy, which are around $120 billion per year.

The Group of 20 (G20) countries, an international forum for governments and central bank governors from 20 major economies, have agreed to phase out fossil subsidies over "the medium term," but progress has been slow and no specific target date has been set. In 2014 almost 30 countries, including Egypt, Indonesia, and India, implemented some form of fossil-fuel subsidy reform (FFSR). Low oil prices made the removal of consumer fossil-fuel subsidies more politically acceptable. As a result, according to IISD, many countries that maintain subsidies to oil, gas, diesel, coal, and electricity generated from such fuels will be considering or undergoing reform in the near future.

Meanwhile, many countries are ramping up their commitment toward renewable energy. Germany and other European countries use feed-in tariffs (discussed further below), a form of subsidy to solar energy. The United States spent more than any other country on renewable energy subsidies, around $15 billion in 2013. China provided about $2 billion, although this figure is likely too low as it does not include the value of low-interest loans offered for renewable energy projects by state-owned banks.

Sources: Morales, 2010; IISD, 2014; U.S. EIA, 2015b.

fossil-fuel use that began with coal in the eighteenth century was a one-time, unrepeatable bonanza—the rapid exploitation of a limited stock of high-quality resources, with increasingly negative effects on planetary ecosystems.[4]

The fossil-fuel age has obviously brought significant economic progress to much of the world, but this particular route to development cannot be followed universally. If everyone consumed fossil fuels at the rate of the average American, global greenhouse gas emissions would increase by about a factor of four. Fortunately, the earth receives enough solar energy every hour to supply all human energy needs for an entire year.[5] This figure is theoretical—the capture and use of solar energy, either directly or indirectly through such sources as wind power or biomass, involves costs and limitations. Nonetheless, renewable energy potential is very great. Operating our economies on this renewable flow, as opposed to non-renewable fossil fuels, represents a key component of any conception of sustainable development.

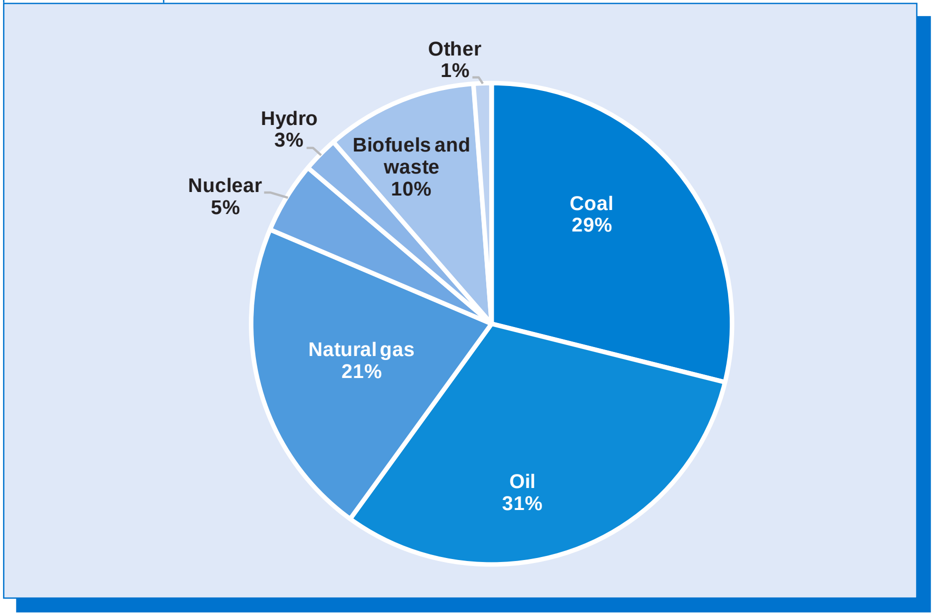
> **capital stock** the existing quantity of capital in a given region, including manufactured, human, and natural capital.

Because so much of the **capital stock** and infrastructure of modern economic systems are based on fossil-fuel energy use, any transition from fossil fuel dependence will involve massive restructuring and new investment. While private markets will play a critical role in this process, major changes in government policies are necessary to foster the transition. The considerable economic implications of this justify a special focus on energy use as a central economic and environmental issue.

11.2 EVALUATION OF ENERGY SOURCES

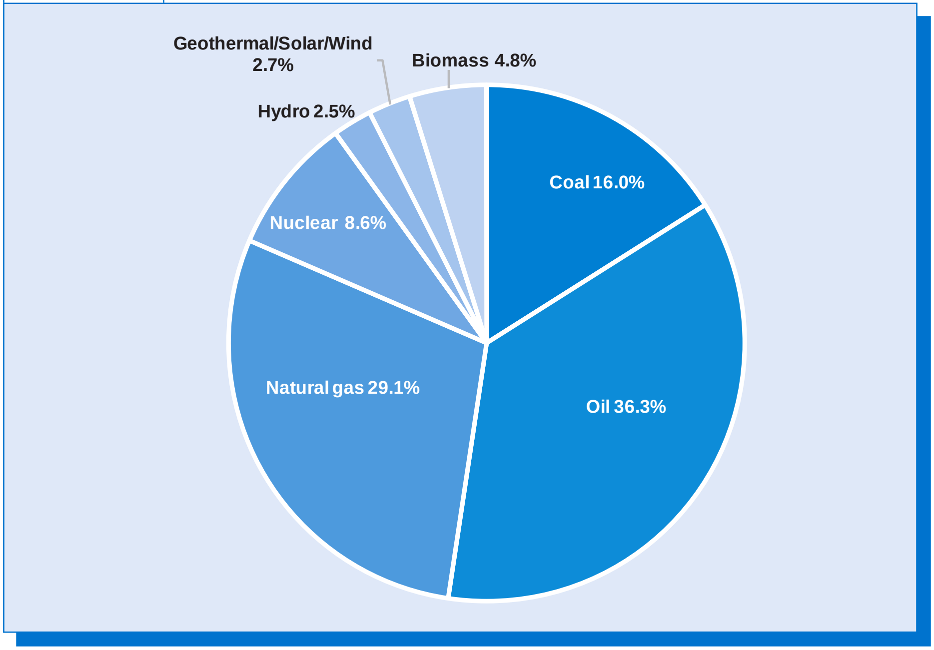
We obtain energy from numerous sources for many different purposes. Figure 11.1 shows the main energy sources consumed globally. We see that over 80 percent of the world's energy

Figure 11.1 Global Energy Consumption 2013, by Source



Source: International Energy Agency, 2015.

Figure 11.2 United States Energy Consumption 2014, by Source



Source: U.S. Energy Information Administration, 2016.

comes from fossil fuels—oil, coal, and natural gas. In most respects, the energy shares for the United States, shown in Figure 11.2, are similar to the global proportions. The United States is slightly more reliant upon natural gas and nuclear energy, and less reliant upon coal, while the world as a whole has a higher percentage of hydropower. Both the United States and the world receive only about 2–3 percent of energy from renewable, wind, solar, and geothermal, energy (though, as we will see, this currently small percentage is growing at a rapid rate).

One objective of this chapter is to analyze how our energy supply mix will need to change in the future. But first we need to consider how we should evaluate various energy sources. This will help explain why our current energy mix is allocated as shown in Figures 11.1 and 11.2. We consider five criteria to evaluate different energy sources:

1) *Price*: This is perhaps the most obvious factor to consider. We should consider both the average price of a particular energy source and also its variability over time. As you might expect, our heavy reliance on fossil fuels has been driven largely by price considerations.
2) *Availability*: Fossil fuels are limited in supply. We consider later in the chapter whether we are in danger of running out of fossil fuels. Renewable energy sources such as wind and solar cannot be depleted but have variable geographic availability and may fluctuate daily and seasonally.
3) *Environmental impacts*: Analysis of the environmental impacts of different energy sources should consider the full life-cycle impacts. For example, for coal we should look at the impacts associated with mining coal, the air pollution generated from burning coal, the disposal of the waste from coal plants, and the eventual decommissioning of power plants.
4) *Net energy*: It takes energy to get energy. For example, the energy required to explore for, to extract, and to process crude oil should be deducted from the energy obtained to determine the net available energy. Net energy is normally expressed as a ratio of the energy available for final consumption divided by the energy required to produce it.
5) *Suitability*: Different types of energy are more useful for certain applications. For example, oil is particularly suitable for powering motor vehicles, nuclear power is primarily used to generate electricity, and geothermal energy is well suited for heating buildings.

Net Energy and Suitability of Energy Sources

We discuss price, availability, and environmental impacts of energy in more detail later in this chapter. First, we discuss the other two factors: net energy and suitability of energy sources.

If net energy is expressed as a ratio, a higher value means that we can obtain a significant amount of available energy without using much energy to obtain it. Table 11.1 shows the net energy ratios for various energy sources, based on U.S. data. Net energy ratios for fossil fuels range from five for shale oil (oil extracted from hydrocarbon-rich rocks) to 80 for coal. The net energy ratio for hydropower is even greater—over 100. Nuclear power, wind energy, and photovoltaic cells have moderate net energy ratios.

The lowest net energy ratios are found for some biofuels. In fact, the energy needed to produce corn ethanol is about equal to the energy obtained. This implies that without significant technological improvements, corn ethanol is not a very attractive energy option based on the net energy criterion, although other biofuels might achieve higher net energy ratios.

Energy statistics normally divide energy use among four sectors in an economy: transportation, industrial, residential and commercial (excluding electricity), and electricity

Table 11.1 Net Energy Ratios for Various Energy Sources

Energy Source	Net Energy Ratio
Oil (global)	35
Natural gas	10
Coal	80
Shale oil	5
Nuclear	5–15
Hydropower	>100
Wind	18
Photovoltaic cells	6.8
Ethanol (sugarcane)	0.8–10
Ethanol (corn-based)	0.8–1.6
Biodiesel	1.3

Source: Murphy and Hall, 2010.

(considered as a separate sector). Different energy sources are better suited for different sectors. Table 11.2 shows the three main energy sources used by each sector in the United States.

Transportation is heavily dependent upon oil, which supplies 94 percent of U.S. transportation needs. Oil is well suited for transportation because it has a high energy density and is relatively easy to store. But oil is less prevalent in the other energy sectors. The industrial sector relies about equally on natural gas and oil. Natural gas demands are highest in such industries as chemicals manufacturing, agriculture, and metal manufacturing. The residential and commercial sector relies on natural gas for about three-quarters of its non-electricity energy demands, mainly for heating.

Table 11.2 Energy Consumption by Sector in the United States, 2015

	Sector			
	Transportation	Industrial	Residential and Commercial	Electricity
Percent of total U.S. energy consumption	28%	22%	11%	39%
Primary fuel source	Oil (92%)	Natural gas (44%)	Natural gas (76%)	Coal (37%)
Secondary fuel source	Renewables (5%)	Oil (39%)	Oil (15%)	Natural Gas (26%)
Tertiary fuel source	Natural gas (3%)	Renewables (11%)	Renewables (9%)	Nuclear Energy (22%)
Quaternary fuel source	N/A	Coal (7%)	Coal (1%)	Renewables (13%)
Quinary fuel source	N/A	N/A	N/A	Oil (1%)

Source: U.S. Energy Information Administration, 2016.

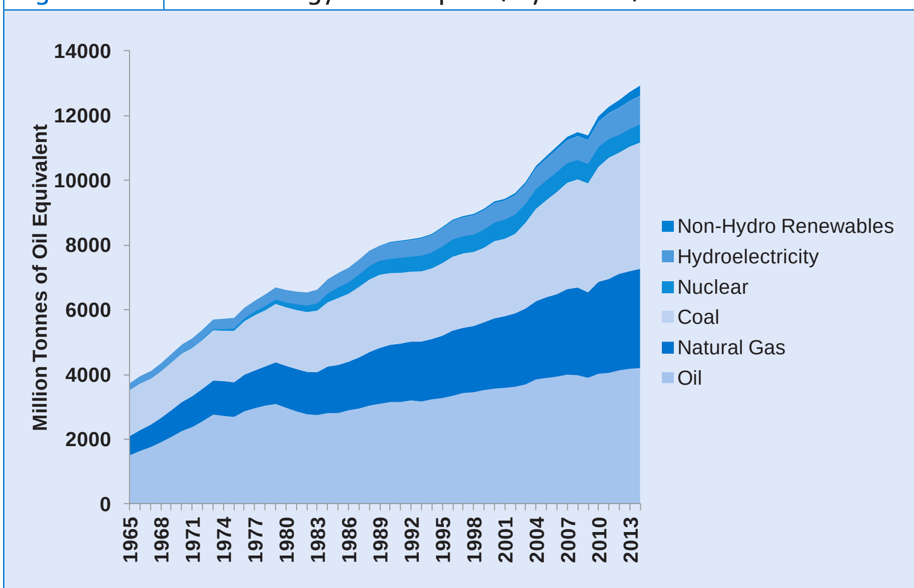
In the electricity sector, the United States gets slightly over one third of its electricity from coal (down from nearly half five years earlier), with 26 percent from natural gas and 22 percent from nuclear power. Renewable energy is most prevalent in electricity generation, with about 13 percent of U.S. electricity coming from renewable sources, mainly hydropower and wind. Wind energy, though starting from a small base as a percent of electric generation, has increased rapidly in recent years. Solar electric generation has also increased rapidly from a small base. We will examine the growth of renewable energy in more detail in Section 4 of this chapter.

11.3 ENERGY TRENDS AND PROJECTIONS

World energy demand has grown rapidly and is expected to continue to grow in the foreseeable future. As seen in Figure 11.3, world energy consumption increased by a factor of more than three between 1965 and 2015. World population approximately doubled during this same period, so about half the growth in global energy demand can be attributed to a higher population and the other half can be attributed to greater demand per capita.

Higher global demand has been met by expanding the use of all forms of energy. From 1965 to 2014, energy consumption from coal increased 172 percent, from oil 178 percent, from hydropower 264 percent, and from natural gas 416 percent. The most rapid growth in recent years has occurred for non-hydro renewables. Since 1990, global consumption of non-hydro renewables has increased by a factor of more than 10. Despite such growth, solar and wind energy currently provide only a small percentage of global energy supplies—less than 2 percent in 2014. Between 2000 and 2015 over 40 percent of the increase in global

Figure 11.3 World Energy Consumption, by Source, 1965–2014



Source: BP Statistical Review of World Energy, 2012–2015.

energy demand was met by expanding coal use, mainly in new electricity plants in emerging countries such as China and India.[6]

But in recent years, renewables have become the leading source of new energy capacity, both in the U.S. and globally. About two thirds of new U.S. energy capacity in 2016 was from renewables. According to a 2015 bulletin from the International Energy Agency, "renewable energy will represent the largest single source of electricity growth over the next five years, driven by falling costs and aggressive expansion in emerging economies."[7]

Projections of future global energy demand depend on assumptions regarding prices, technology, and economic growth. Projections by the major energy agencies, including the U.S. Energy Information Administration and the International Energy Agency (IEA), typically include a baseline, or business-as-usual (BAU), scenario that assumes no significant policy changes and no dramatic shifts in prices and technology. Other scenarios consider what might be expected if, for example, oil prices are significantly higher in the future or if major policy changes are implemented.

Figures 11.4 and 11.5 present one such comparison, produced by the IEA. In the baseline or "current policies" scenario, global energy consumption increases by about 45 percent from 13,559 million tonnes of oil equivalent (Mtoe) to over 19,000 Mtoe in 2040 (a tonne is one metric ton, equal to 1,000 kilograms (kg) or 2,204.6 pounds). Compared to the energy mix shown in Figure 11.1, the percentage of global energy obtained from fossil fuels changes only slightly, from 81 percent to 79 percent (see Figure 11.5). The share of oil is expected to decline, while the share obtained from coal and nuclear is expected to remain about the same. The share from renewable energy increases, but only by about 2 percent.

Figures 11.4 and 11.5 also predict the global energy mix under an aggressive policy scenario intended to keep global warming to no more than 2°C over pre-industrial levels—the target agreed on during the 2015 international meeting on climate change in Paris, corresponding to 450 parts per million of atmospheric CO_2.[8] In this scenario, global energy demand grows by only about 12 percent from 2013 to 2040.

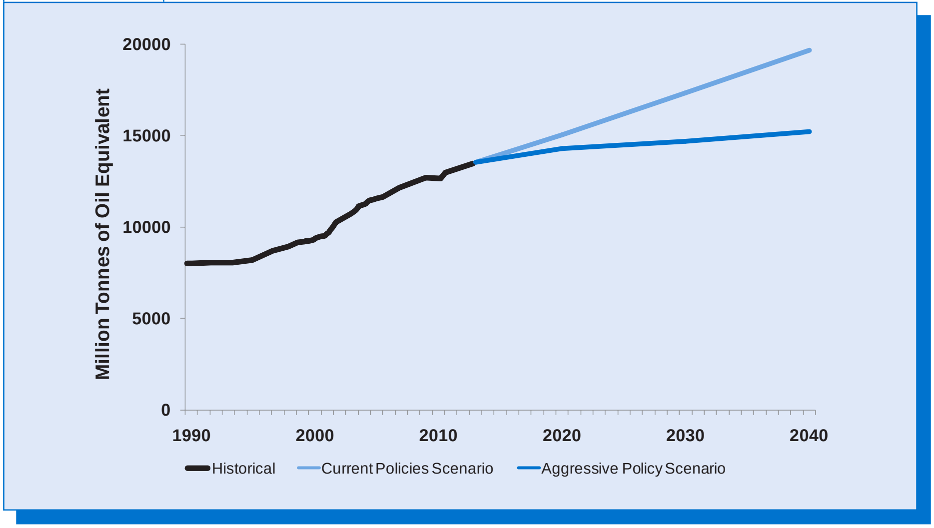
We also see significant differences in the global energy mix (Figure 11.5). Compared to the "current policies" scenario, coal use is dramatically lower, hydro and nuclear have larger shares, and non-hydro renewable energy represents a much larger proportion of global energy use at 25 percent. In this case, the share of global energy obtained from fossil fuels falls from 81 percent to 60 percent. Total global fossil fuel use declines about 15 percent below 2013 levels by 2040, as compared to an increase of 43 percent in the "current policies" scenario. CO_2 emissions decline even further, by nearly 40 percent, due to the shift away from coal.

These results demonstrate that our energy future is not predetermined, but that total energy consumption and the energy supply mix will depend on the policy choices made in the coming years. In fact, concerted policy efforts can make dramatic changes in a relatively short period of time (see Box 11.2).

In addition to looking at energy statistics based on different energy sources, it is also instructive to analyze energy consumption across different countries and regions. As we see in Table 11.3, energy use per capita varies tremendously across countries.

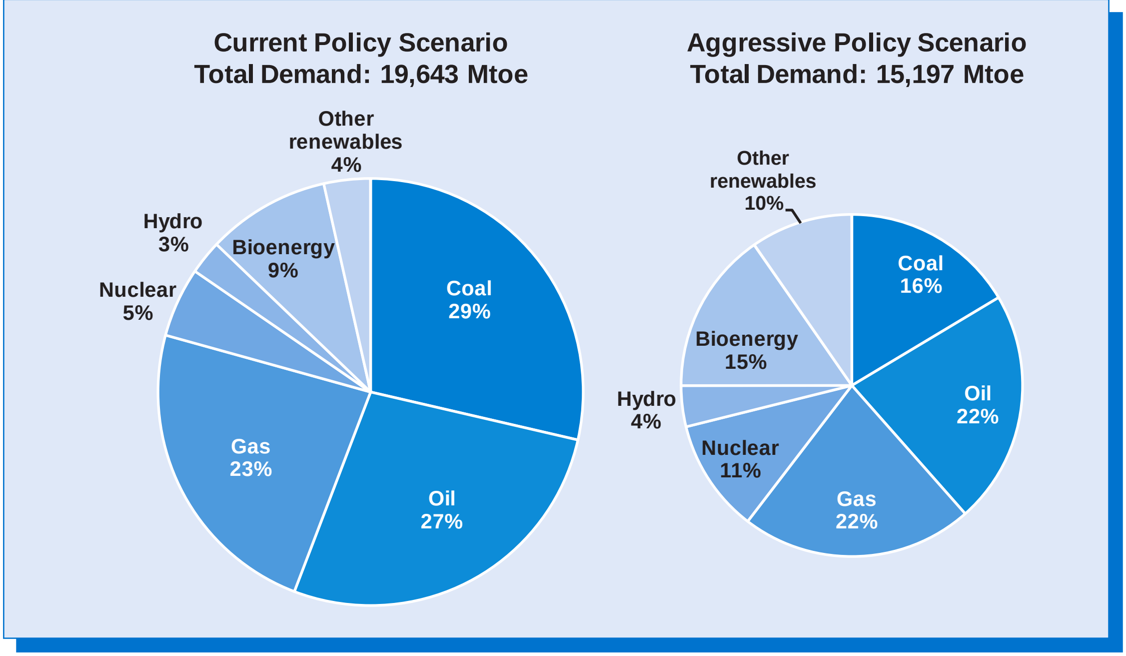
Countries with the highest per capita energy use tend to be either countries with a cold climate, such as Canada, or oil-producing countries such as the United Arab Emirates. Per capita energy use in the United States is relatively high, especially when compared with European countries such as France and Italy. Per capita energy use in China has grown rapidly in recent years, but it is still only about one-quarter of the typical energy use of a U.S. resident. Energy use per person in India is only about one-sixteenth the U.S. level, and energy use in the poorest countries is less than 1 percent of the U.S. level.

Figure 11.4 Projected 2035 Global Energy Demand



Source: International Energy Agency, 2015a.

Figure 11.5 World Primary Energy Demand by Fuel and Scenario, 2040



Source: International Energy Agency, 2015a.

Developed (OECD) countries have historically been responsible for most of global energy demand, but this is changing. Developing (non-OECD) countries have recently surpassed developed countries in total energy consumption, as shown in Figure 11.5. Almost all future growth in global energy demand is expected to occur in developing countries, under the BAU scenario shown in Figure 11.5. Even with such rapid growth in

Box 11.2
PORTUGAL GIVES ITSELF A CLEAN-ENERGY MAKEOVER

Back in 2005 Portugal initiated an ambitious program to increase its reliance on renewable energy. The results have been impressive—the share of Portugal's electricity coming from renewable energy increased from 17 percent in 2005 to 63 percent in 2014. Over that time period, the energy obtained from wind power increased by a factor of seven.

Portugal was able to expand its use of renewable energy rapidly because it had large supplies of untapped wind and hydroelectric power. As it previously relied heavily on costly imports of fossil fuels for its electricity, Portugal's shift toward renewable energy required no tax or debt increases. Portugal now plans to begin closing down some of its conventional power plants that are no longer needed. Portugal is also putting in place a national grid of charging stations for electric cars.

"I've seen all the smiles—you know: It's a good dream. It can't compete. It's too expensive," said Prime Minister José Sócrates. Mr. Sócrates added, "the experience of Portugal shows that it is possible to make these changes in a very short time."

Source: Rosenthal, 2010; Publico, "23% Guaranteed Renewable Electric Consumption in Portugal in 2014," https://www.publico.pt/ecosfera/noticia/renovaveis-garantiram-63-do-consumo-electrico-em-portugal-em-2014-1681364.

Table 11.3 Energy Consumption per Capita, Selected Countries, 2011

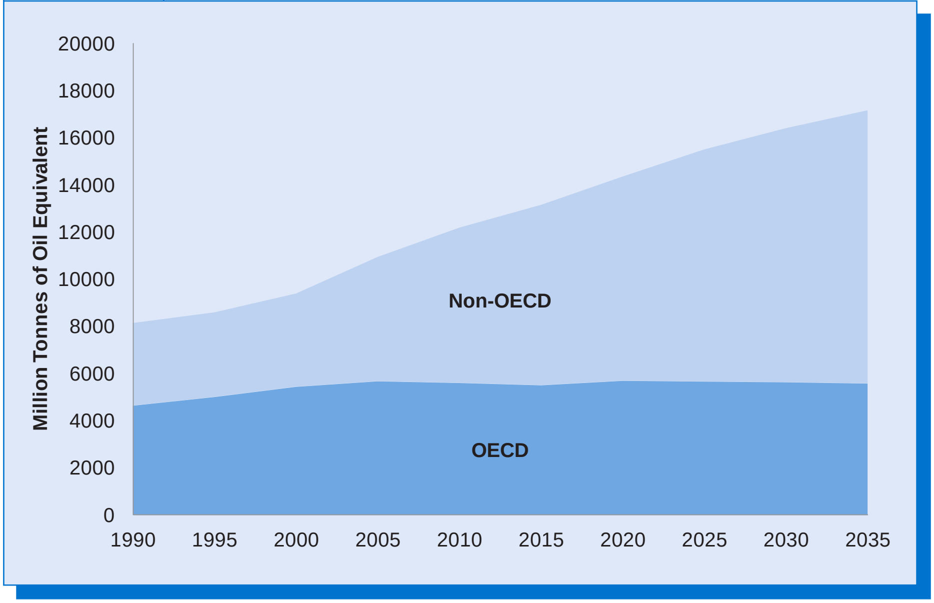
Country	Million BTUs per Person
United Arab Emirates	728
Canada	394
United States	313
Sweden	236
Russia	213
France	166
Germany	165
United Kingdom	134
Italy	123
China	78
Thailand	74
Brazil	60
India	20
Nigeria	5
Ethiopia	2

Source: U.S. Energy Information Administration, International Energy Statistics online database.

Note: BTU = British thermal unit.

energy consumption in developing countries, energy use per capita will still be only about one-third of the levels in developed countries. Thus global inequality in energy access will continue for the foreseeable future.

Figure 11.6 Past and Projected Energy Consumption, OECD vs. Non-OECD Nations



Source: BP Energy Outlook 2016.

Note: OECD = Organization for Economic Cooperation and Development (OECD are primarily industrialized countries, while non-OECD are developing countries.)

11.4 ENERGY SUPPLIES: FOSSIL FUELS

Even with aggressive energy policies, global energy demand is projected to continue to increase in the coming decades, and we will continue to meet most of our energy needs with fossil fuels for some time. But is the supply of fossil fuel sufficient to meet future demands? And can existing supplies of fossil fuels be burned without inviting environmental disaster?

Much of the discussion about energy supplies has focused on oil. In the early years of the twenty-first century, there was a focus on the concept of "peak oil"—the idea that limited oil supplies would lead to rising prices and force a reduction in oil consumption. Prices did indeed rise from 2000 to 2012. But the introduction of "unconventional" oil sources produced by hydraulic fracturing of rock and extraction from tar sands and oil shales led to an increase in oil supply and falling prices (see Figure 11.7). Whether this trend will be maintained, or whether prices will rise again, cannot be easily predicted. How can we evaluate projections of oil supply limits?

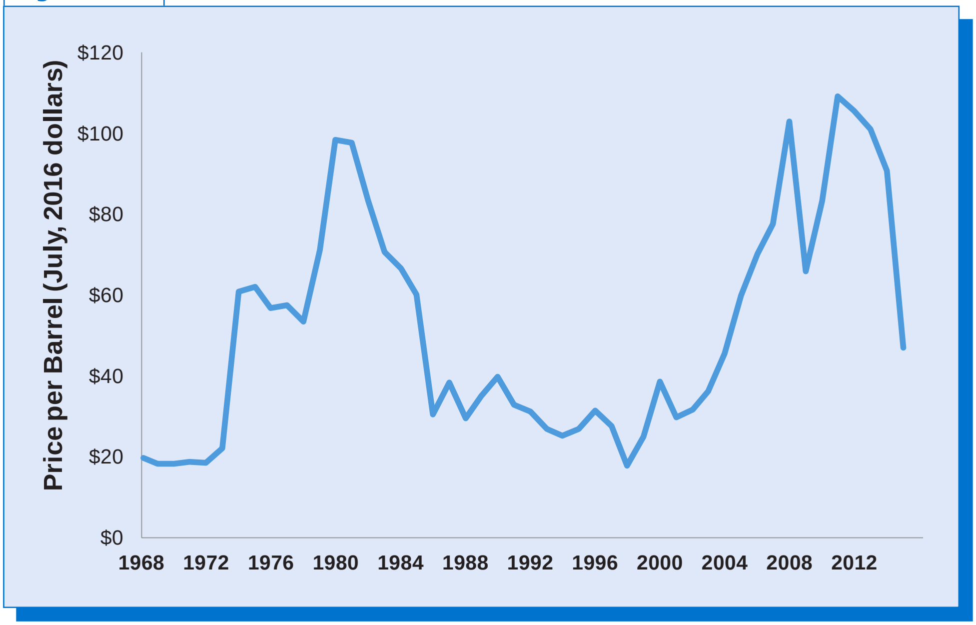
According to a theory advanced by petroleum geologist M. King Hubbert in 1956, the typical pattern of oil production over time resembles a bell curve. In the early period of resource exploitation, discovery and production expand, leading to falling prices and exponentially rising consumption. Eventually production becomes more expensive as the most-accessible supplies are depleted. New discoveries decline, and production eventually peaks. Beyond the peak, production falls and, assuming constant or increasing demand, prices continue to increase.

Hubbert curve a bell-shaped curve showing the production quantity of a nonrenewable energy resource over time.

As Figure 11.8 shows, the **Hubbert curve** projection for U.S. crude oil production matched up rather well to the actual data through about 2010. Conventional oil output in the United States peaked in the early 1970s and has generally declined since then. But the recent increase in U.S. output, due to "unconventional" oil production, has changed this trend. Figure 11.8 also shows U.S. oil consumption. While the United

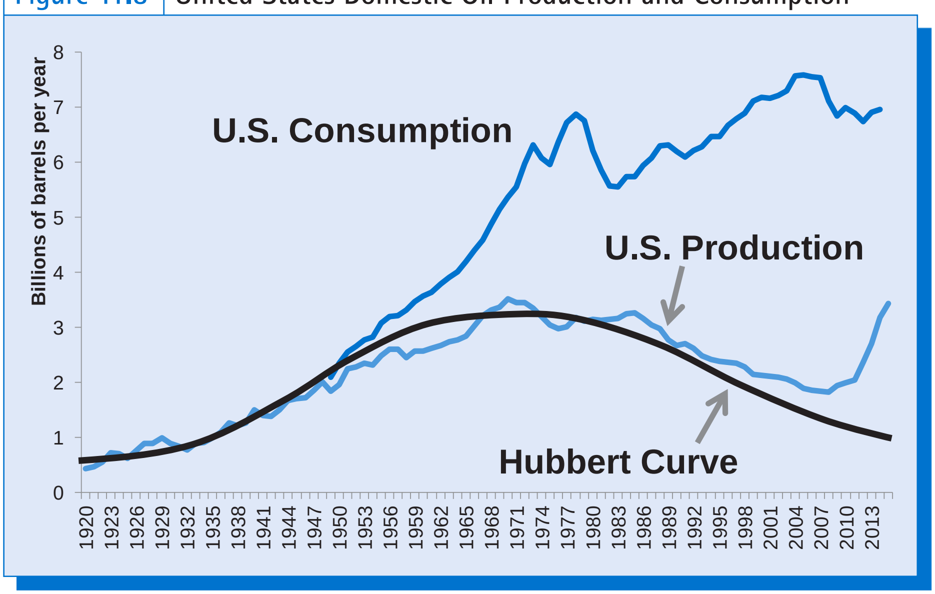
States was essentially oil independent until about 1950, the share of oil demand met from imports generally increased after the 1950s. In the mid-2000s the United States obtained over 60 percent of its oil from imports. But with the rise in unconventional oil production, the proportion of imports has fallen, to about 50 percent in 2015.

Figure 11.7 Oil Prices in Constant Dollars, 1970–2015



Sources: U.S. Energy Information Administration, www.eia.gov and http://inflationdata.com.

Figure 11.8 United States Domestic Oil Production and Consumption



Source: U.S. Energy Information Administration, Annual Energy Outlook online database.

Note: The trend of declining U.S. crude oil production continued through 2008, with an increase after 2009 resulting from increased production of "unconventional" sources, such as deep offshore oil and shale oil.

A common myth is that the United States obtains most of its imported oil from the Middle East. Actually, the top exporter of oil to the United States, with about 39 percent of all U.S. imports, is Canada. Other top sources of U.S. oil imports are Saudi Arabia (13 percent), Venezuela (10 percent), Mexico (9 percent), and Colombia (5 percent).

Current projections by the U.S. Energy Information Administration estimate that U.S. domestic crude oil production will hold steady or increase in the coming decades.[9] So while the Hubbert curve may continue to be representative of conventional U.S. crude oil production, the availability of unconventional oil sources may prevent further declines in U.S. total oil production.

Global Oil Supplies

More important is the availability of oil supplies at the global level. Table 11.4 shows that in 1980 proven oil reserves would have been sufficient to meet 31 years of demand if demand levels stayed constant. Rather than staying constant, global demand for oil continued to increase. But did the world run out of oil in 2011, or earlier? Of course not. We see in Table 11.4 that oil reserves are now 65 percent higher than they were in 1980 as a result of new discoveries, technological improvements, and higher oil prices, which have made more oil deposits economically viable. Even with higher global demand, proven reserves could now meet global demands for a further 50 years at current consumption rates.

Figure 11.9 shows past and projected global oil production under a scenario that takes into account recent pledges by countries to reduce greenhouse gas emissions and phase out subsidies for fossil fuel. Even with new discoveries, conventional crude oil production stabilizes at around 70 million barrels per day. Global oil production is able to continue to increase through reliance on unconventional oil sources and natural gas liquids.

When global oil production peaks might depend as much upon policy as on resource availability. According to the IEA:

> Clearly, global oil production will peak one day, but that peak will be determined by factors affecting both demand and supply. . . . [I]f governments act more vigorously than currently planned to encourage more efficient use of oil and the development of alternatives, then demand for oil might begin to ease soon and, as a result, we might see a fairly early peak in oil production. That peak would not be caused by resource constraints. But if governments do nothing or little more than at present, then demand will continue to increase, supply

Table 11.4 Global Oil Reserves, Consumption, and Resource Lifetime, 1980–2011

Year	Proven Reserves (Billion Barrels)	Annual consumption (Billion Barrels)	Resource Lifetime (Years)
1980	683	22	31
1985	803	22	37
1990	1,028	24	42
1995	1,066	26	42
2000	1,258	28	45
2005	1,357	31	44
2010	1,622	32	51
2015	1,698	34	51

Source: British Petroleum, 2016.

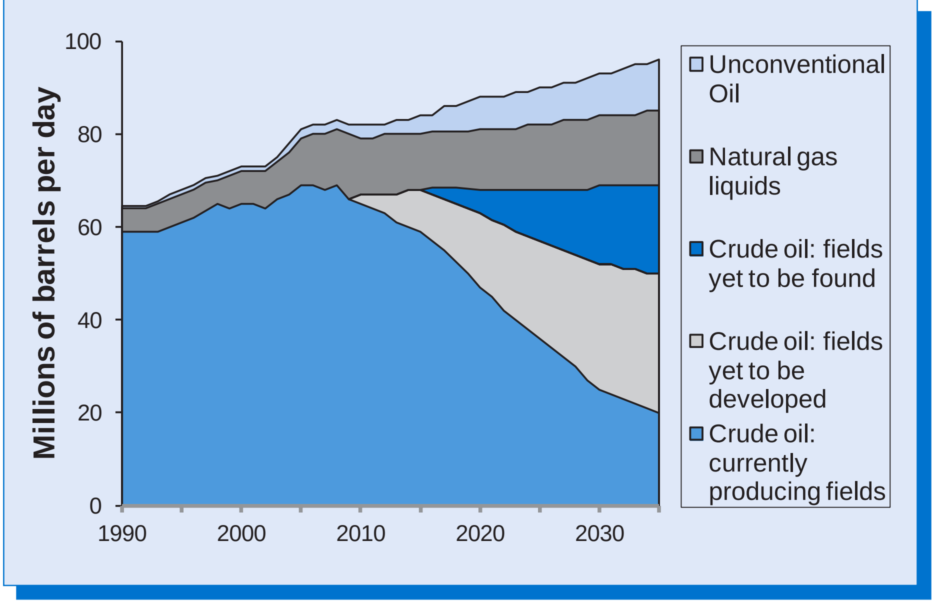
> costs will rise, the economic burden of oil use will grow, vulnerability to supply disruptions will increase and the global environment will suffer serious damage.
>
> Unconventional oil is set to play an increasingly important role in world oil supply through to 2035, regardless of what governments do to curb demand. . . . Unconventional oil resources are thought to be huge—several times larger than conventional oil resources. The rate at which they will be exploited will be determined by economic and environmental considerations, including the costs of mitigating their environmental impact. Unconventional sources of oil are among the more expensive available. Consequently, they play a key role in setting future oil prices.[10]

So in an absolute sense, we are unlikely to run out of oil anytime soon, especially when unconventional sources are taken into account. But sources such as tar sands and shale oil tend to have significantly higher environmental impacts than conventional oil. Currently these impacts are not reflected in market prices, but, as we know, economic theory suggests that the higher environmental costs should be internalized, which would make these unconventional sources more expensive.

Globally, oil demand is still rising. Given the suitability of oil for the transportation sector, there is a steady increase in demand for oil in developing countries:

> All of the net increase in oil demand comes from the transport sector in emerging economies, as economic growth pushes up demand for personal mobility and freight. Alternative vehicle technologies emerge that use oil much more efficiently or not at all, such as electric vehicles, but it takes time for them to become commercially viable and penetrate markets.[11]

Figure 11.9 **Past and Projected Global Oil Production, 1990–2035**



Source: International Energy Agency, 2010.

Note: Estimates of ultimately recoverable global oil vary widely, and the year of projected "peak oil" production depends on these estimates. The study shown above indicates a peak in conventional production by 2010, with production from current fields falling off rapidly thereafter. Future oil production depends on discovery of new fields, natural gas liquids, and "unconventional" sources such as shale oil.

Economic factors, however, may lead to substitution of other fuels for oil, and concerns about global climate change, discussed in Chapters 12 and 13, may promote policies to favor renewables over oil.

Other Fossil Fuels: Natural Gas and Coal

The other fossil fuels, coal and natural gas, are potential alternatives to oil in the transportation sector. Natural gas can be used to fuel vehicles directly; there were an estimated 5 million natural gas vehicles worldwide in 2011.[12] Coal can be used to generate electricity to fuel electric vehicles. As we saw in Table 11.1, coal and natural gas play a relatively large role in the industrial, residential, commercial, and electricity sectors. Globally, coal and natural gas provide nearly 50 percent of energy supplies. What about the availability of these resources?

Both coal and natural gas are more abundant than oil in the United States and globally. While the United States has only 3 percent of global oil reserves, it has 5 percent of the world's natural gas reserves and 27 percent of coal reserves. In recent years, the United States has experienced a natural gas boom, with an increase in production of 50 percent between 2005 and 2015. According to the U.S. Energy Information Administration, U.S. production of natural gas is expected to grow by about 1 percent per year over the next couple of decades.[13]

Box 11.3 TAINTED WATER AND EARTHQUAKES LINKED TO HYDRAULIC FRACTURING FOR NATURAL GAS

In 2011 a report published by the U.S. Environmental Protection Agency (EPA) found that the hydraulic fracturing of rocks in the process of drilling for natural gas, commonly known as fracking, is the likely cause of contaminated water supplies in Wyoming. The report raises questions about the environmental safety of fracking, which is being used to extract previously unrecoverable natural gas in dozens of places around the United States. However, the energy industry claims that water contamination from fracking has not been conclusively proven.

The report is based on a three-year study initiated when local residents complained about the smell and taste of their water. The study site, known as the Pavillion field, is a natural gas well that is unusually shallow. The shallow depth means that natural gas can seep upward into underground aquifers, contaminating water supplies.

Another potential threat from fracking is the chemicals companies use to extract natural gas, which can also contaminate water supplies. While Wyoming now requires companies to disclose the ingredients in their fracking fluids, in other states disclosure is not required. The EPA has begun a national study of the effects of fracking on drinking water supplies.

In Oklahoma, a new Federal hazard map shows that parts of the state are now as earthquake-prone as California, due to the effects of widespread fracking. Scientists say Oklahoma's increase in quakes results from the injection of billions of barrels of salty wastewater from oil and natural gas exploration. Wastewater injection has put pressure on the state's fault lines, leading to quakes that have damaged homes, schools, and other structures.

Sources: Johnson, 2011; Josh Sanburn, "Oklahoma is Now as Much of an Earthquake Risk as California," *Time*, March 28, 2016.

Natural gas is generally viewed as the cleanest fossil fuel, producing comparatively low amounts of air pollutants and greenhouse gases. Yet environmentalists have expressed concerns in recent years over the process of hydraulic fracturing, or "fracking," to obtain natural gas (see Box 11.3). Some analysts have suggested that leakages of methane, a powerful greenhouse gas, can make fracked natural gas as bad as or worse than coal in terms of greenhouse gas emissions.[14] Globally, natural gas reserves are sufficient for more than 50 years of supply at current demand levels.[15]

Coal is the most environmentally damaging fossil fuel. It is estimated that particulate-matter pollution from coal power plants leads to the deaths of more than 13,000 people in the United States every year.[16] Coal also emits more carbon dioxide, the primary greenhouse gas, per unit of energy. Coal is, however, the most abundant fossil fuel. The United States is the world leader in coal reserves—its reserves alone could satisfy current world demand for 31 years. Global reserves are sufficient for 114 years of world consumption at current demand levels.[17] But burning this much coal would be likely to create disastrous climate change effects, as we will discuss in Chapters 12 and 13, as well as considerably increased ground-level pollution, especially in countries such as China where air pollution is already severe.

11.5 RENEWABLE ENERGY SOURCES

In one sense, renewable energy is unlimited, as supplies are continually replenished through natural processes. As noted earlier, the daily supply of solar energy is theoretically sufficient to meet all human energy needs for an entire year. But solar energy and other renewable energy sources are limited in the sense that their availability varies geographically and across time. Some regions of the world are particularly well suited for wind or solar energy. For example, solar energy potential is highest in the southwestern United States, northern Africa, the Middle East, and parts of Australia and South America. Some of the best regions for wind energy include northern Europe, the southern tip of South America, and the Great Lakes region of the United States. Geothermal energy is abundant in countries such as Iceland and the Philippines.

One important question is whether renewable energy is available in sufficient quantities to replace our dependence on fossil fuels while also being comparably reliable and suitable for different purposes (we consider the issue of cost in the next section). A recent study concluded that renewable energy sources, based on wind, water, and sunlight (WWS), could provide all new energy globally by 2030 and replace all current nonrenewable energy sources by 2050.[18] Table 11.5 shows estimates of the potential energy from various renewable energy sources, converted into trillions of watts. Projected global energy demand in 2030 is 17 trillion watts. Thus we see in Table 11.5 that the availability of energy from wind and solar in likely developable locations is more than sufficient to meet all the world's energy needs. The report authors' analysis envisions

> a world powered entirely by WWS, with zero fossil-fuel and biomass combustion. We have assumed that all end uses that feasibly can be electrified use WWS power directly, and that the remaining end uses use WWS power indirectly in the form of electrolytic hydrogen (hydrogen produced by splitting water with WWS power). The hydrogen would be produced using WWS power to split water; thus, directly or indirectly, WWS powers the world.[19]

The authors then estimate the infrastructure that would be necessary to supply all energy worldwide from WWS in 2030. Table 11.6 presents their results, based on the assumption that 90 percent of global energy is supplied by wind and solar and 10 percent by other

Table 11.5 Availability of Global Renewable Energy

Energy Source	Total Global Availability (Trillion Watts)	Availability in Likely Developable Locations (Trillion Watts)
Wind	1700	40–85
Wave	> 2.7	0.5
Geothermal	45	0.07–0.14
Hydroelectric	1.9	1.6
Tidal	3.7	0.02
Solar photovoltaic	6500	340
Concentrated solar power	4600	240

Source: Jacobson and Delucchi, 2011a.

renewables. They also consider the land requirements for renewable **energy infrastructure**, including the land for appropriate spacing between wind turbines. Land requirements total about 2 percent of global land area, with most of this space between wind turbines that could be used for agriculture, grazing land, or open space. Also, wind turbines could be located offshore to reduce the land requirements.

energy infrastructure a system that supports the use of a particular energy source, such as the supply of gas stations and roads that support the use of automobiles.

The technology already exists to implement these renewable energy sources. Effective deployment of greatly increased renewable energy supply will require upgrading the electric grid as well as new capacity to store and transfer power (see Box 11.4). While construction of this renewable energy infrastructure will require significant investment, the authors conclude that the primary hurdles are not economic. "Barriers to the plan are primarily social and political, not technological or economic. The energy cost in a WWS world should be similar to that today."[20]

Table 11.6 Infrastructure Requirements for Supplying All Global Energy in 2030 from Renewable Sources

Energy Source	Percent of 2030 Global Power Supply	Number of Plants/Devices Needed Worldwide
Wind turbines	50	3,800,000
Wave power plants	1	720,000
Geothermal plants	4	5,350
Hydroelectric plants	4	900
Tidal turbines	1	490,000
Rooftop solar photovoltaic systems	6	1.7 billion
Solar photovoltaic power plants	14	40,000
Concentrated solar power plants	20	49,000
Total	100	

Source: Jacobson and Delucchi, 2011a.

Box 11.4

INTERMITTENCY AND CAPACITY ISSUES WITH RENEWABLES

While renewable energy supplies have huge potential, their availability varies by time and location. They therefore cannot be matched to demand as easily as fossil fuels. Wind power depends on the speed of the wind at any given time. The availability of sunshine for solar power is greatest at certain times of day, and can be limited by cloudy weather. Also, most renewable energy sources have relatively low capacity factors compared to fossil fuels.

The supply-demand matching problem is most significant in the electricity market, where supply must continually match demand. While fossil fuel plants can be scheduled to start and stop at times of anticipated demand change, the output of solar and wind facilities cannot be increased on demand. As power systems move to a higher percentage of renewable sources, supply management policies must be developed to deal with energy-source **intermittency**.

Energy diversity is one response to intermittency. For example, solar energy is strongest in the summer, while in most places wind energy is strongest in the winter. A combination of the two can provide more consistent year-round electricity generation than either one individually.

Power storage is another option. Solar houses can store electricity in batteries. Battery storage must be at least sufficient for nights, ideally with some additional storage for cloudy days and/or periods of high electricity use. This same technology could be deployed on a broader scale, with individual buildings having on-premises battery storage. Renewable energy could be taken from the grid as it was available, and used as needed. The cost of delivered energy would then be the cost of production plus the cost of battery storage.

On a grid scale, electricity storage is more frequently accomplished with pumped water storage. When excess electricity is available from the grid, water is pumped from a lower reservoir to a higher reservoir. When electricity is needed, the water is allowed to flow back down and generate electricity. This is the same technology used in hydroelectric plants, but with water and energy able to move in both directions.

In combination with excess capacity, a robust national (and possibly international) electric grid is another approach to intermittency. Though the wind may not blow in a particular place at a particular time, wind is likely blowing somewhere all the time. An electric grid can be used to move energy from where it is being produced to where it is needed. But moving large amounts of electricity over long distances requires a substantial electricity grid. Policies that support modernized grid development will be needed to facilitate increased renewable energy utilization.

Source: Timmons *et al.*, 2017.

The issue of cost is central to the question of whether an energy transition will occur and, if so, how rapidly. The availability of energy supplies, whether fossil fuels or renewables, is not the determining factor. Rather, it is the relative costs, including the cost of energy infrastructure investment and the cost of day-to-day energy supply. In analyzing costs, we should consider both the market cost of supply and the environmental costs of various energy sources. It is to this analysis that we now turn.

intermittency a characteristic of energy sources such as wind and solar, which are available in different amounts at different times.

11.6 THE ECONOMICS OF ALTERNATIVE ENERGY FUTURES

The world currently gets about 80 percent of its energy supplies from fossil fuels because these sources generally provide energy at the lowest cost. However, the cost advantage of fossil fuels over renewable energy sources has been decreasing in recent years, and certain renewables can already compete with fossil fuels on solely financial terms. The price of fossil fuels, especially for oil, in the future is difficult to predict, while the costs of renewable energy are expected to decline further. Thus even without policies to promote a transition toward renewables, economic factors are currently moving us in that direction.

Comparing the costs of different energy sources is not straightforward. Capital costs vary significantly—a new nuclear power plant can cost \$5 billion to \$8 billion. Some energy sources require continual fuel inputs, while other sources, such as wind and solar, only require occasional maintenance. We also need to account for the different lifespans of various equipment and plants.

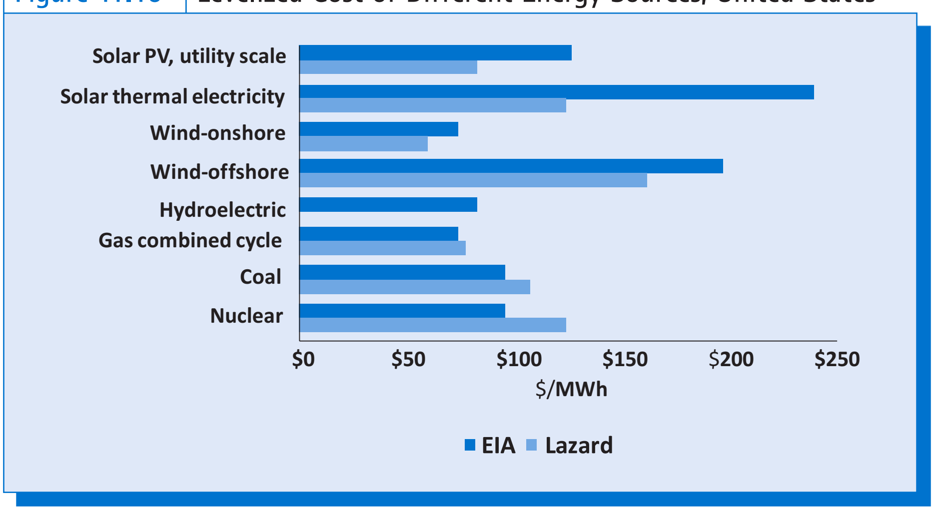
Cost comparisons between different energy sources are made by calculating the **levelized cost** of obtaining energy. Levelized costs represent the **present value** of building and operating a plant over an assumed lifetime, expressed in real terms to remove the effect of inflation. For energy sources that require fuel, assumptions are made about future fuel costs. The levelized construction and operations costs are then divided by the total energy obtained to allow direct comparisons across different energy sources.

Different studies have produced different estimates of the costs of various energy sources. Some of these differences are attributed to cost variations in different regions of the world. Figure 11.10 provides a comparison of the projected levelized costs of generating electricity in the United States, from two different sources providing a range of estimates.

levelized costs the per-unit cost of energy production, accounting for all fixed and variable costs over a power source's lifetime.

present value the current value of a stream of future costs or benefits; a discount rate is used to convert future costs or benefits to present values.

Figure 11.10 Levelized Cost of Different Energy Sources, United States



Sources: Lazard, 2014; U.S. EIA, 2016b.

Note: Lazard values are midpoints of estimated ranges.

Box 11.5
ELECTRIC VEHICLES BECOMING COST COMPETITIVE

Electric Vehicles (EVs) are starting to penetrate the automobile market. A step beyond hybrids and plug-in hybrids, which use both gasoline and electric power, fully-electric vehicles use electricity only. According to a 2015 analysis by the Union of Concerned Scientists, over a vehicle's lifetime EVs produce less than half the greenhouse gas emissions of a typical vehicle. As a greater share of electricity is generated from renewable sources, the environmental benefits of EVs will increase further. With fewer moving parts, EVs also require less maintenance. For example, EVs require no oil changes or tune-ups, and have no exhaust systems, belts, or complex transmissions. Another advantage of EVs is lower fuel costs. According to the U.S. Department of Energy, a Nissan Leaf (a fully electric vehicle) owner will save over $3,700 in fuel costs over five years compared to an average gas vehicle.

EVs are generally more expensive to purchase than comparable gas vehicles, primarily due to the high cost of the batteries. However, the cost savings from reduced maintenance and fuel costs means that total vehicle ownership costs tend to be less for EVs. For example, a 2013 analysis finds that for most drivers the total five-year ownership costs of an EV is lower than the cost of a traditional gas car or hybrid. Also, EV battery costs are rapidly declining—dropping by 65 percent between 2010 and 2015. With expected further declines in battery prices, EVs may soon become cost-competitive with gas vehicles based on purchase price alone. Once this occurs, "electric vehicles will probably move beyond niche applications and begin to penetrate the market widely, leading to a potential paradigm shift in vehicle technology."

EVs still comprise only about 1 percent of all new vehicle sales globally. But global EV sales increased by 80 percent in 2015, with much of that growth in China and Western Europe. Depending on such factors as the decline in battery costs and increased range due to greater battery capacity, the expansion of charging infrastructure, and government incentives, EVs could comprise a much larger share of vehicle sales in the future—35 percent by 2040 according to one analysis.

Norway is an example of how government incentives can dramatically boost the sales of EVs. EV owners in Norway are exempt from purchase taxes, including a 25 percent value-added tax, as well as paying road tolls and parking fees. EV drivers can use bus lanes and have access to an extensive network of free charging stations. As a result, EV registrations in Norway increased by a factor of five between 2012 and 2015. In 2015 EVs comprised about 25 percent of all new vehicle registrations in Norway, far exceeding EV sales rates in other countries.

Sources: Nealer *et al.*, 2015; EPRI, 2013; Frankfurt School-UNEP Collaborating Centre and Bloomberg New Energy Finance, 2016; Nykvist and Nilsson, 2015, quote from p. 330; Edelstein, 2016; Bloomberg New Energy Finance, 2016; Bjerkan *et al.*, 2016; Barnato, 2016, Lifetime emissions estimate for 2016 Nissan Leaf from https://www.fueleconomy.gov/.

Though there is some variation in estimates, it appears that onshore wind power is fully competitive with coal, natural gas, and nuclear. (Natural gas is currently the cheapest fossil fuel, displacing coal.) Hydroelectric power is also competitive. Solar photovoltaic at utility scale is cheaper than coal according to one set of the estimates, while a bit more expensive based on the EIA estimate. Solar thermal electricity and offshore wind are more expensive, though solar thermal approaches competitiveness according to the lower estimate.

Oil does not appear in Figure 11.10 because it is rarely used to generate electricity. In the United States, only about 0.5 percent of electricity is generated using petroleum products. But as we saw in Table 11.2, oil dominates the transportation sector. Various alternative options are available for road vehicles, including fully-electric vehicles, plug-in hybrids which use fossil fuels only for long-distance trips, and, potentially, hydrogen fuel cells. The electricity to charge vehicles or generate hydrogen could be generated by wind power, solar energy, geothermal power, or other renewable sources.

Cost comparisons between traditional internal combustion vehicles and renewable energy alternatives depend on such factors as the price of gasoline, the price of electricity, and the availability of tax credits or rebates for clean vehicles. A recent review of studies comparing the costs of different vehicle energy options finds that renewable alternatives, particularly using wind energy to power batteries of electric vehicles, may already be cost competitive with traditional vehicles, even in the United States, where gasoline is relatively cheap.[21] (See Box 11.5.)

Looking to the future, it is reasonable to expect that the cost of renewables will continue to decline, while the future price of fossil fuels is highly uncertain. Consider the past and projected cost trends for wind and solar energy in Figures 11.11 and 11.12. Particularly with solar PV, we can be confident that its cost will continue to decline. Note the more rapid recent decrease in solar costs since 2009 shown in Figure 11.13. As technologies improve and prices decline, the utilization of these energy sources is increasing rapidly. (See Figure 11.14.)

Not only are the costs of renewable energy sources expected to decline in the future, but Figures 11.11 and 11.12 also indicate that cost range will decrease for wind and solar energy. Thus the future prices for renewable energy are expected to be predictable within a relatively narrow band. This is not the case for fossil fuels, particularly oil. The price of oil depends on technology and future discoveries, and it is also highly dependent on political factors and other world events. The price of coal and natural gas normally does not vary as much as that of oil, but the future costs of these are also highly unpredictable.

Given the declining costs of renewables, it is possible that fossil fuels will, in the future, lose their price advantage over renewables. According to a report by Bloomberg New Energy Finance, solar will "emerge as the least-cost generation technology in most countries by 2030." The report foresees wind and solar accounting for 64 percent of new generating capacity to be installed over the next 25 years. [22]

Figure 11.11 Declining Past and Future Price Range for Solar Energy

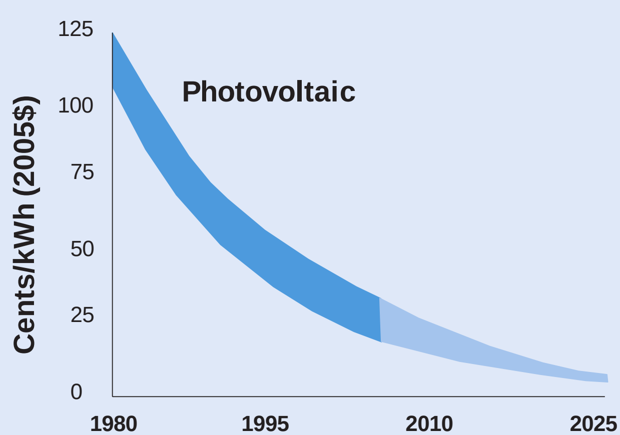
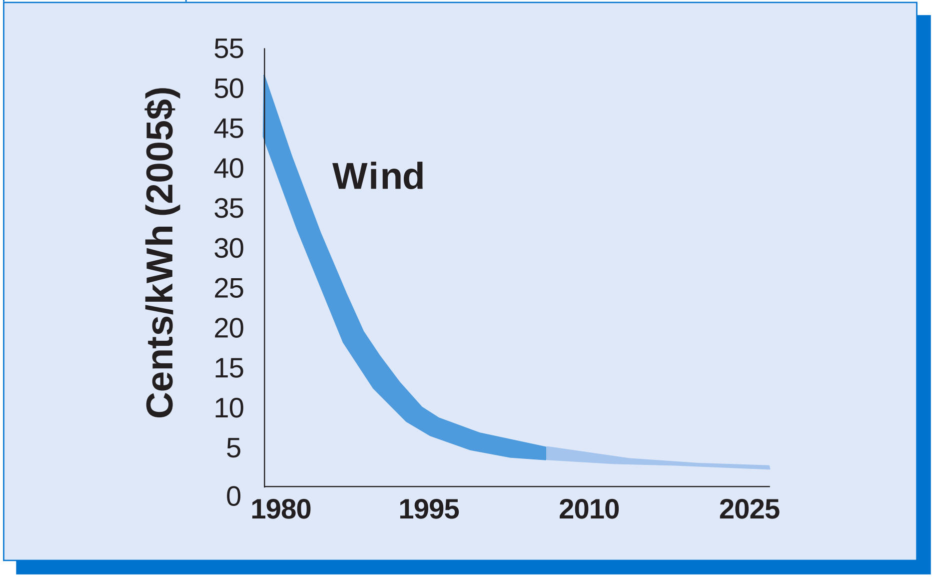


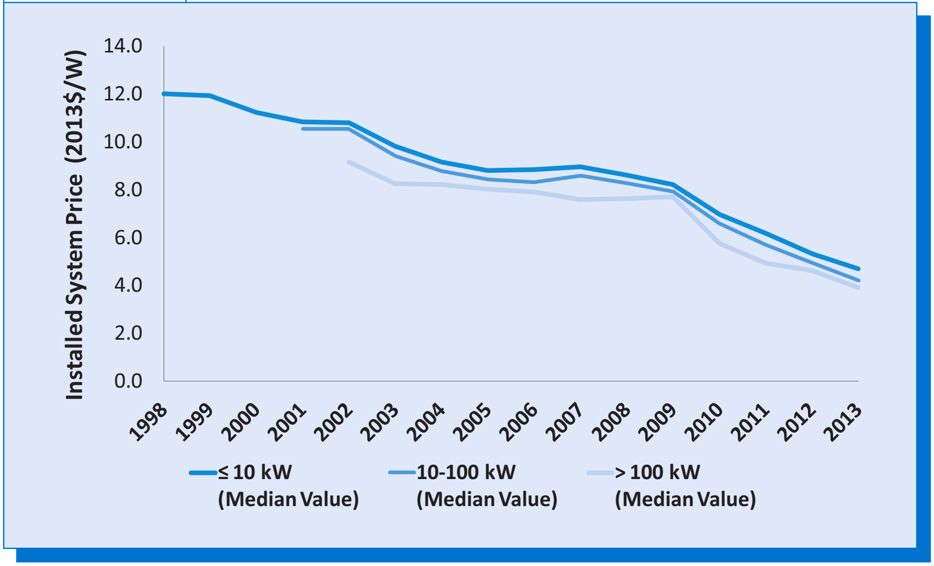
Figure 11.12 Declining Past and Future Price Range for Wind Energy



Source: National Renewable Energy Laboratory, Renewable Energy Cost Trends, www.geni.org/globalenergy/library/energytrends/renewableenergy-cost-trends/renewable-energy-cost_curves_2005.pdf.

Note: kWh = kilowatt hours.

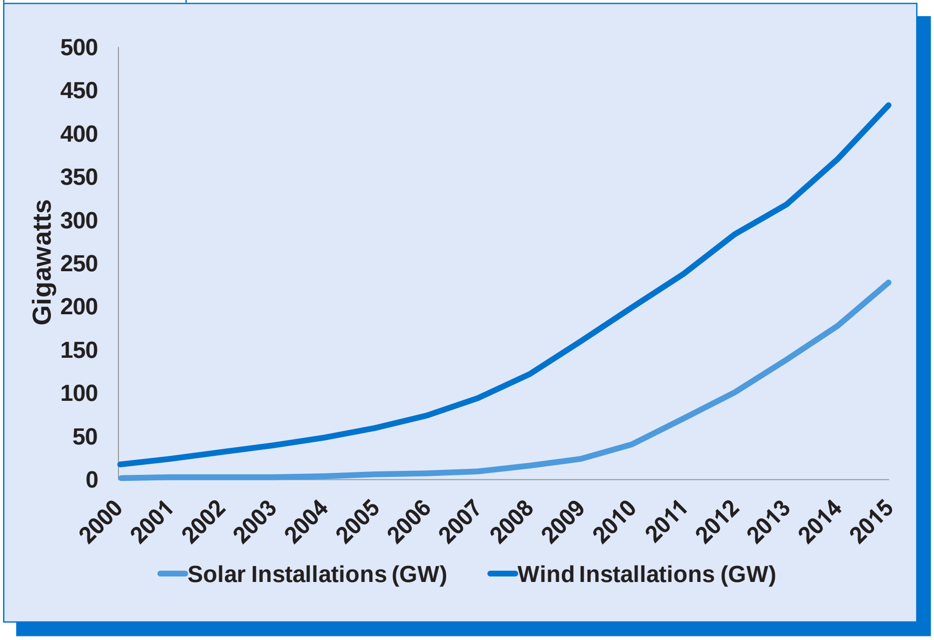
Figure 11.13 Recent Trends in Solar Prices



Source: Barbose *et al.*, 2014.

Whether this forecast of an increasing shift to renewables comes true depends largely on market cost competitiveness. So far, however, we have been comparing the costs of different energy sources based on current market prices. But we also need to consider two other factors that affect current and future energy prices: energy subsidies and environmental externalities.

Figure 11.14 Growth in Global Solar and Wind Power, 2003–2012



Source: Renewables 2016 Global Status Report, http://www.ren21.net/wp-content/uploads/2016/06/GSR_2016_KeyFindings1.pdf. For data before 2005, Renewables 2013 Global Status Report.

Energy Subsidies

Energy subsidies can take various forms, including:

- *Direct payments or favorable loans*: A government can pay a company a per-unit subsidy for producing particular products or provide them with a loan at below-market interest rates.
- *Tax credits and deductions*: A government can allow individuals and businesses to claim tax credits for actions such as installing insulation or purchasing a fuel-efficient vehicle. **Depletion allowances** are a form of tax credit widely used for oil production.
- *Price supports*: For example, the price that producers of renewable energy receive may be guaranteed to be at or above a certain level. **Feed-in tariffs**, commonly used in Europe, guarantee producers of solar and wind power a certain rate for sales of power to the national grid.
- *Mandated purchase quotas*: These include laws requiring that gasoline contain a certain percentage of ethanol or that governments buy a certain percentage of their energy from renewable sources.

As we saw in Chapter 3, subsidies can be justified to the extent that they support goods and services that generate positive

depletion allowances a tax deduction for capital investments used to extract natural resources, typically oil and gas.

feed-in tariffs a policy to provide renewable energy producers long-term contracts to purchase energy at a set price, normally based on the costs of production (but higher than the cost of production).

externalities. All energy sources currently receive a degree of subsidy support, but, as discussed in Box 11.1, subsidies heavily favor fossil fuels. Given that fossil-fuel use tends to generate negative, rather than positive, externalities, it is difficult to justify large current fossil fuel subsidies on the basis of economic theory. Directing the bulk of energy subsidies to fossil fuels tilts the playing field in their favor relative to renewables.

In 2009, the members of the G20, a group of major economies including both developed and developing countries, agreed to "rationalize and phase out over the medium term inefficient fossil-fuel subsidies that encourage wasteful consumption" and "adopt policies that will phase out such subsidies worldwide."[23] The International Energy Agency notes:

> Energy subsidies—government measures that artificially lower the price of energy paid by consumers, raise the price received by producers or lower the cost of production—are large and pervasive. When they are well-designed, subsidies to renewables and low-carbon energy technologies can bring long-term economic and environmental benefits. However, when they are directed at fossil fuels, the costs generally outweigh the benefits. [Fossil-fuel subsidies] encourage wasteful consumption, exacerbate energy-price volatility by blurring market signals, incentivize fuel adulteration and smuggling, and undermine the competitiveness of renewables and other low-emission energy technologies.[24]

Global subsidies to fossil fuels in the electricity sector total about $100 billion annually.[25] Data on subsidies to nuclear power are difficult to obtain, but the limited information available suggests global nuclear subsidies of at least $10 billion. In addition, there are implicit subsidies to the nuclear industry related to limiting accident liability. The Price-Anderson Act in the United States limits nuclear operator liability to less than half a billion dollars, although the potential costs of a major accident could be much greater. Global subsidies to renewable forms of electricity total about $30 billion annually but are growing faster than other subsidies.

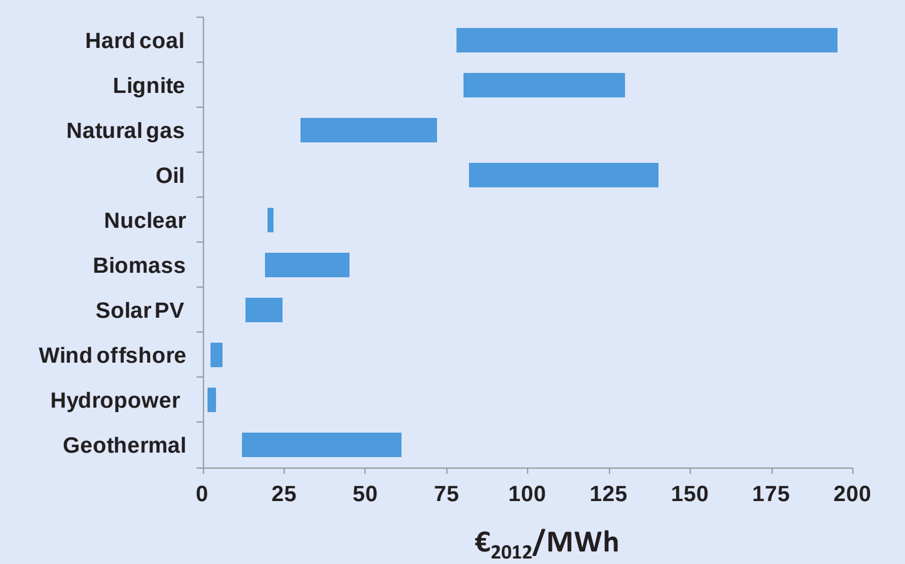
While the majority of electricity-sector subsidies go to fossil fuels and nuclear, on a per-kilowatt-hour basis the current subsidy structure favors renewables. Since renewables currently represent a small percentage of electricity generation, the per-unit subsidy for renewables is significantly greater than for fossil fuels. Subsidies effectively lower the price of electricity provided by fossil fuels by about one cent per kilowatt-hour. But according to one estimate, subsidies in 2007 lowered the per-kilowatt-hour price of wind energy by 7 cents, of concentrated solar energy by 29 cents, and of solar PV by 64 cents.[26] Thus electricity-sector subsidies are generally encouraging a shift to renewables.

In the transportation sector, global oil subsidies averaged about $212 billion annually in 2011.[27] With annual global oil consumption around 1.3 trillion gallons, this amounts to a subsidy of about $0.15 per gallon. If we assume that this value is applicable for the United States, oil subsidies approximately cancel out the federal gasoline tax of 18 cents per gallon. The other major recipient of subsidies in the transportation sector is biofuels. Global subsidies to biofuels are estimated at about $20 billion and growing rapidly.

Environmental Externalities

In addition to subsidy reform, economic theory also supports internalizing externalities. The price of each energy source should reflect its full social costs. Various studies of energy externalities suggest that if the price of all energy sources included externality costs, a transition toward renewables would already be much further along.

Figure 11.15 Externality Cost of Various Electricity-Generating Methods, European Union



Source: European Commission, 2014.

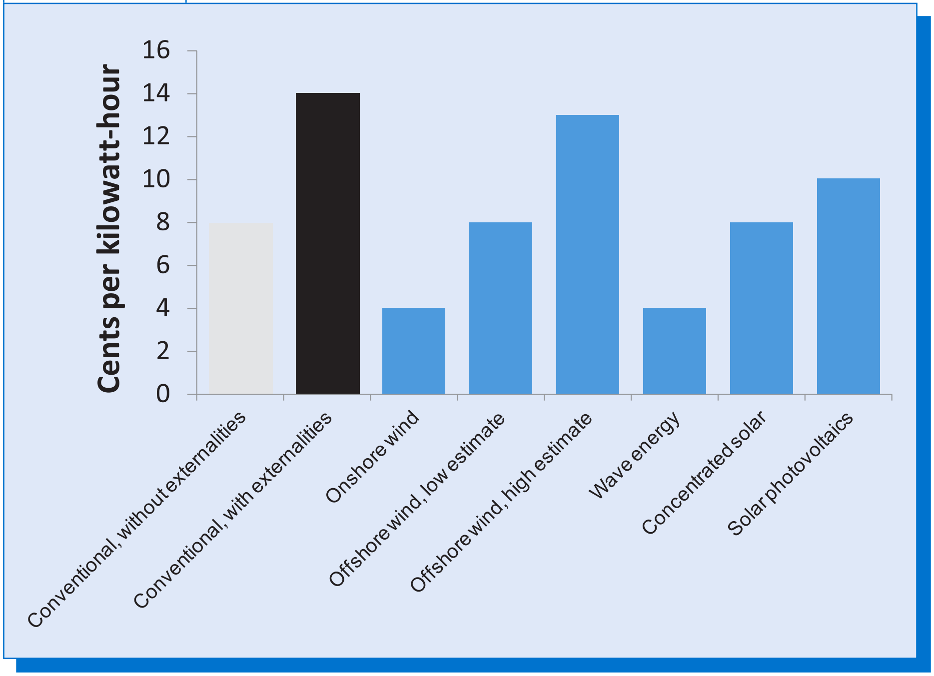
Figure 11.15 provides a summary of the range of external costs associated with different electricity sources, based on European analyses. The externality cost of coal is particularly high, ranging between 80 and 200 euros per megawatt-hour (between 8 and 20 eurocents per kilowatt hour). Other studies on coal externalities in the United States indicate costs of about 6 cents per kilowatt-hour.[28] Oil has external costs of around 80–140 euros per megawatt-hour. The externalities associated with natural gas are lower, but still range between 30 and 75 euros per megawatt-hour, a result that is also consistent with U.S. estimates.

The externality costs associated with renewable energy are much lower, less than 10 euros per megawatt-hour (1 eurocent per kilowatt-hour) for wind and hydropower, and around 25 euros/MWh (2.5 eurocents/KWh) for solar PV. So while fossil fuels may currently have a cost advantage over renewables based solely on market prices, if externalities were included, several renewables would likely become the most affordable energy sources—in particular, onshore wind, geothermal, and biomass energy. Similarly, the cost advantage of oil in transportation would likely disappear if externalities were fully included in the price.[29]

The operating externalities of nuclear energy are relatively low, as the life cycle of nuclear power generates low levels of air pollution and greenhouse gas emissions. But the potentially most significant externalities from nuclear power are the risks of a major accident and the long-term storage of nuclear wastes. These impacts are difficult to estimate in monetary terms (remember the analysis in Chapter 7 of the assessment of risk and uncertainty). Whether nuclear power will play an increased or decreased role in future energy supplies remains a controversial topic (for more on the debate over nuclear energy, see Box 11.6).

Our discussion suggests that the biggest factor currently preventing a transition to renewable energy is the failure to account for externalities. Getting the prices "right" would send a clear signal to businesses and consumers that continued reliance on fossil fuels is bad

Figure 11.16 Projected Cost of Electricity-Generating Approaches, 2020



Source: Jacobson and Delucchi, 2011b.

economics. According to a 2015 study by the International Monetary Fund, while global pre-tax subsides to fossil fuels amount to about \$333 billion, this figure rises to as much as \$5 *trillion* when externality costs are included.[30] But even without full internalization of externalities, the declining cost of renewables means that a transition from fossil fuels will occur in the future.

Figure 11.16 shows a projected comparison of the cost of electricity generation in 2020 using traditional fossil-fuel methods and various renewable alternatives, with and without externality costs included. Based solely on production costs without externalities, the renewable sources of onshore wind, wave energy, concentrated solar, and potentially offshore wind are all expected to be cost competitive with fossil fuels. When the impacts of externalities are fully included, all renewable sources become less expensive than fossil fuels. These results imply that there are good economic reasons for promoting a transition to renewables. In the final section of this chapter, we turn to policy proposals to encourage a more rapid transition.

11.7 POLICIES FOR THE GREAT ENERGY TRANSITION

What kinds of government policies are most important to foster a timely and efficient transition to a shift to renewable energy sources? As discussed, one policy goal agreed on by many of the world's largest countries is to phase out inefficient fossil-fuel subsidies. One concern is that in the short term this could lead to higher energy prices and a decrease in economic

Box 11.6
NUCLEAR POWER: COMING OR GOING?

In the 1950s nuclear power was promoted as a safe, clean, and cheap source of energy. Proponents of nuclear power stated that it would be "too cheap to meter" and predicted that nuclear power would provide about one-quarter of the world's commercial energy and most of the world's electricity by 2000 (Miller, 1998).

Currently, nuclear power provides only about 4.4 percent of the world's primary energy consumption and about 11 percent of the world's electricity. Most of the world's capacity to produce nuclear power predates 1990. The decommissioning of older plants, which had an expected lifespan of 30 to 40 years, has already begun. However, some people have called for a "nuclear renaissance," mainly because carbon emissions from the nuclear power life cycle are much lower than with fossil fuels.

The catastrophic 2011 Fukushima accident in Japan caused many countries to reconsider their nuclear power plans. As Japan reevaluates its use of nuclear power, Germany has decided to phase out the use of nuclear power entirely by 2022. In Italy, the debate over nuclear power was put to voters, with 94 percent rejecting plans for an expansion of nuclear power. But other countries are moving ahead with plans to expand their use of nuclear power, particularly China. Currently 20 nuclear plants are under construction in China. Other countries moving ahead with expanded use of nuclear power are India, Russia, and South Korea.

Thus the role of nuclear power in the future global energy mix remains uncertain. The Fukushima accident has slightly lowered baseline projections of future energy supplies from nuclear power. While some see the accident as evidence that we need to focus more on renewables like wind and solar, others worry that a decline in nuclear power will result in "higher energy costs, more carbon emissions and greater supply uncertainty."

Sources: Macalister, 2011; World Nuclear Association, "Nuclear Power in China," http://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx; Nuclear Energy Institute, "World Statistics," http://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics.

growth. But the money that governments save could be invested in ways that would reduce the cost of renewable alternatives and encourage a more rapid transition from fossil fuels. According to a study by the International Institute for Sustainable Development

> fossil fuel subsidy reform would result in aggregate increases in gross domestic product (GDP) in both OECD and non-OECD countries. The expected [increase is as high as] 0.7 per cent per year to 2050. . . . Results from a wide variety of global and single-country economic modeling studies of subsidy reform suggest that on an aggregate level, changes to GDP are likely to be positive, due to the incentives resulting from price changes leading to more efficient resource allocation.[31]

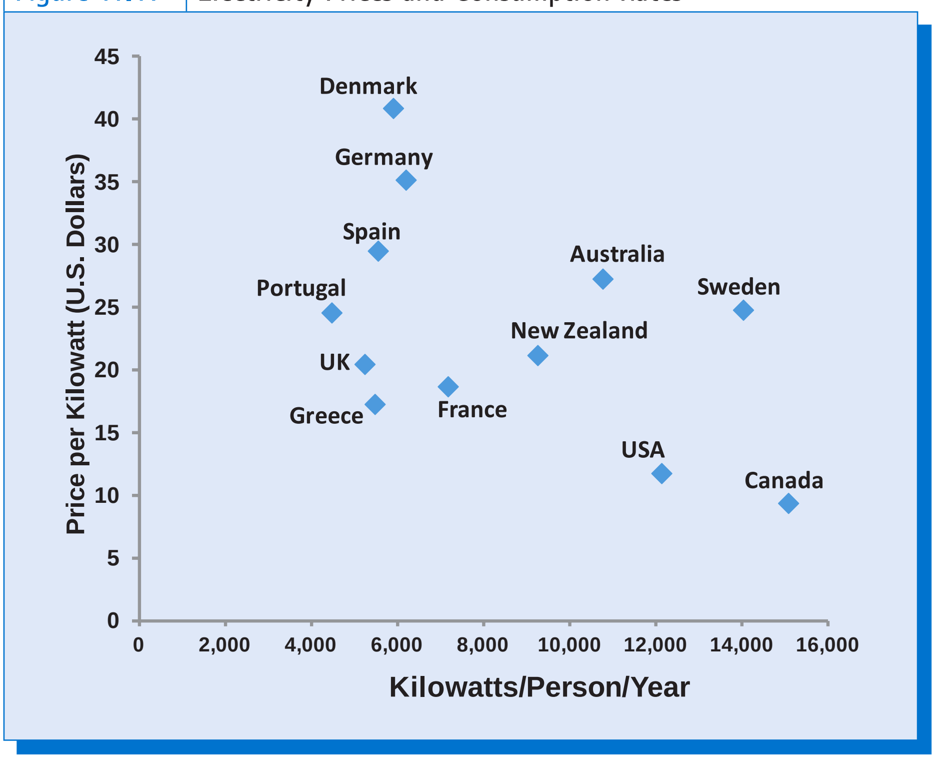
One major issue is the need to internalize the negative externalities of different energy sources. A common form of Pigovian tax is a tax on gasoline. Even though governments use this tax primarily to raise revenue, it also serves the function of internalizing externalities. While the price of crude oil is determined in a global market, the retail price of gasoline varies widely across countries due to differences in gasoline taxes. In 2016 the price of gasoline ranged from less than $1 per gallon in countries such as Venezuela, Saudi Arabia, and Kuwait, where gas is subsidized rather than taxed, to as much as $6 per gallon in France, Norway, the United Kingdom, and other countries where gas is heavily taxed.[32]

Economic theory suggests that the "correct" tax on gas should fully account for the negative externalities. In the United States, the current federal gas tax is 18.4 cents per gallon, in addition to state taxes that range from 8 to 50 cents per gallon. Virtually all economists agree that these taxes are too low, although there is disagreement about how much higher the tax should be. While some economists suggest it should be only about 60 cents higher, others suggest that gas taxes should be over $10 per gallon to fully reflect all external costs.[33]

Pigovian taxes can also be applied to the electricity sector. As we see in Figure 11.17, electricity prices vary across countries, primarily due to variations in tax rates. In general, higher electricity prices are associated with lower per capita consumption rates. For example, the United States has relatively low electricity prices and relatively high consumption rates. Electricity prices in Germany, Spain, and Denmark are much higher, and per capita consumption rates are about half the rate of the United States. But we need to be careful about drawing conclusions based on a simple comparison like this because it fails to account for many other variables that could influence electricity demand other than prices, such as income levels, climate, and the availability of different heating options. For example, Sweden has both higher electricity prices and higher consumption rates than the United States. Explaining this difference would require additional information not presented in Figure 11.17.

Beyond reducing fossil-fuel subsidies and implementing externality taxes, other policy options to encourage a transition to renewable energy include:

Figure 11.17 Electricity Prices and Consumption Rates



Sources: U.S. Energy Information Administration, International Energy Statistics database; International Energy Agency, Energy Prices and Statistics online database.

1. Energy research and development
2. Feed-in tariffs
3. Subsidies for renewable sources, including favorable tax provisions and loan terms
4. Renewable energy targets
5. Efficiency improvements and standards

Increasing research and development (R&D) expenditures will speed the maturation of renewable energy technologies. Public energy R&D expenditures have been increasing in recent years, from $10 billion in 2000 to $17 billion in 2014.[34] Countries that invest heavily in energy R&D will likely gain a competitive advantage in this area in the future.

> Those nations—such as China, Brazil, the United Kingdom, Germany and Spain—with strong, national policies aimed at reducing global warming pollution and incentivizing the use of renewable energy are establishing stronger competitive positions in the clean energy economy. Nations seeking to compete effectively for clean energy jobs and manufacturing would do well to evaluate the array of policy mechanisms that can be employed to stimulate clean energy investment. China, for example, has set ambitious targets for wind, biomass and solar energy and, for the first time, took the top spot within the G-20 and globally for overall clean energy finance and investment in 2009. The United States slipped to second place. Relative to the size of its economy, the United States' clean energy finance and investments lag behind many of its G-20 partners. For example, in relative terms, Spain invested five times more than the United States last year, and China, Brazil and the United Kingdom invested three times more.[35]

Feed-in tariffs guarantee renewable energy producers access to electricity grids and long-term price contracts. For example, homeowners who install solar PV panels can sell excess energy back to their utility at a set price. Feed-in tariff policies have been instituted by dozens of countries and several U.S. states. The most ambitious is in Germany, which has become the world's leader in installed solar PV capacity.

Feed-in tariffs are intended to be reduced over time as renewables become more cost competitive with traditional energy sources. A reduction in feed-in tariff rates has already begun in Germany. A 2008 analysis by the European Union of different approaches for expanding the share of renewables in electricity supplies found that "well-adapted feed in tariff regimes are generally the most efficient and effective support schemes for promoting renewable electricity."[36]

Subsidies can take the form of direct payments or other favorable provisions, such as tax credits or low-interest loans. As mentioned earlier, the bulk of current subsidies goes to fossil fuels. Yet subsidies make more sense for developing, rather than mature, technologies. Subsidies for renewable energy can promote economies of scale that lower production costs. Like feed-in tariffs, output subsidies can be gradually reduced as renewables become more competitive.

Renewable energy targets set goals for the percentage of total energy or electricity obtained from renewables. More than 60 countries have set renewable energy targets. The European Union has set a goal of 20 percent of total energy from renewables by 2020, with different goals for each member country. The 2020 targets include goals of 18 percent for Germany, 23 percent for France, 31 percent for Portugal, and 49 percent for Sweden. All EU countries have adopted national renewable energy action plans showing what actions they intend to take to meet

renewable energy targets regulations that set targets for the percentage of energy obtained from renewable energy sources.

their renewables targets. EU countries have also agreed on a new renewable energy target of at least 27 percent of final energy consumption in the EU as a whole by 2030.[37]

While the United States does not have a national renewable goal, most states have set goals. Some of the most ambitious goals include California and New York (50 percent by 2030), Hawaii (100 percent by 2045), and Vermont (75 percent by 2032).[38]

energy demand-side management an energy policy approach that seeks to reduce energy consumption through policies such as information campaigns or higher energy prices.

Most of the discussion in this chapter has focused on energy supply-side management—adjusting the energy supply mix to include a greater share of renewable sources. However, **energy demand-side management** is generally considered the most cost effective and environmentally beneficial approach to energy policy. In other words, while shifting a kilowatt of energy supply from coal to solar or wind is desirable, eliminating that kilowatt of demand entirely is even better. As the U.S. Environmental Protection Agency has noted:

> Improving energy efficiency in our homes, businesses, schools, governments, and industries—which consume more than 70 percent of the natural gas and electricity used in the country—is one of the most constructive, cost-effective ways to address the challenges of high energy prices, energy security and independence, air pollution, and global climate change.[39]

In some cases, energy efficiency improvements can be obtained by technological changes, such as reducing fossil fuel use by driving a hybrid car or fully electric vehicle. Improving energy efficiency in machinery, appliances, and buildings has the potential to reduce energy use by 40–60 percent. In other cases, energy efficiency means changing behavior, such as washing clothes in cold water, drying clothes on a clothesline instead of a clothes dryer, or switching off lights and appliances when not in use. The potential for demand-side management to reduce the projected growth of energy consumption is particularly important in reducing fossil fuel use, since the lower total demand for energy becomes, the larger the proportion of the remaining needed energy that can be supplied by renewables.

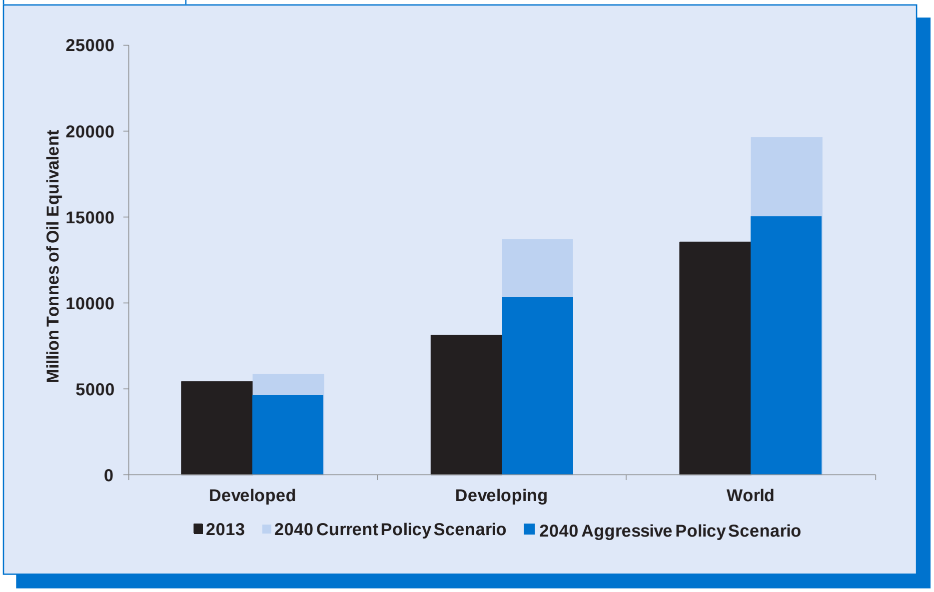
Under a "business-as-usual" (BAU) scenario, the International Energy Agency (IEA) has projected that global energy demand will increase by 44 percent over 2013 levels by 2040. But with greater energy efficiency, the IEA projects only a 12 percent increase in global energy demand by 2040. In developed countries, energy demand could actually decrease relative to current levels. In developing countries, energy consumption would still increase, but only by about 28 percent, instead of by 69 percent under a BAU scenario. (See Figure 11.18—this is consistent with the scenarios shown earlier in Figure 11.4 and Table 11.3.)

Realizing such gains from energy efficiency will require substantial investment, estimated at about 0.2 percent of global GDP.[40] However, investments in energy efficiency are typically much cheaper than meeting demand growth through developing new energy supplies. Well-designed energy efficiency programs cost, on average, only about half the cost of providing new energy supplies.[41] Another analysis estimates the cost of energy efficiency at 0 to 5 cents per kilowatt-hour ($0 to $50 per megawatt-hour).[42] Comparing this estimate to the cost of energy sources in Figure 11.10, we see that improving energy efficiency is the most economical option for addressing energy demand.

In addition to expanding R&D, two other policies can be effective at promoting energy efficiency. One is to set energy **efficiency standards**. Fuel-economy standards are one example. After about twenty years in which fuel-economy standards were little changed, in 2011 the Obama administration announced new standards that would raise the average fuel efficiency of new vehicles to 54.5 mpg

economic efficiency standards an environmental regulation approach that sets minimum standards for efficiency, such as electricity or fuel consumption.

Figure 11.18 Global Potential for Energy Efficiency



Sources: Based on Blok *et al.*, 2008; updated data from IEA, 2015a.

in 2025. Compared to 2010 model year vehicles, total fuel savings for 2025 vehicles would total more than $8,000 over the lifetime of the vehicle. Tighter standards have also been proposed for heavy trucks. Fuel efficiency for automobiles improved by about 5 miles per gallon between 2005 and 2015, from 19.5 to 24.5 mpg.[43] Other energy efficiency standards exist for buildings, appliances, electronics, and light bulbs.

Efficiency labeling informs consumers about the energy efficiency of various products. For example, in the United States the U.S. Environmental Protection Agency and U.S. Department of Energy manage the Energy Star program. Products that meet high-efficiency standards, above the minimum requirements, are entitled to receive the Energy Star label. About 75 percent of consumers who purchased an Energy Star product indicated that the label was an important factor in their purchase decision. In 2014 the energy savings from Energy Star products totaled about $34 billion.[44]

> **efficiency labeling** labels on goods that indicate energy efficiency, such as a label on a refrigerator indicating annual energy use.

Even with informative labels, many consumers do not purchase high-efficiency products because the upfront costs may be higher. For example, light-emitting diode (LED) and compact fluorescent light bulbs cost more than traditional incandescent light bulbs. However, the energy savings from efficient bulbs means that the additional cost will be recovered in a relatively short period, normally less than one year. While people may resist buying efficient bulbs for other reasons, one problem is that people often have high implicit discount rates, focusing on the upfront cost while discounting the long-term savings (see Box 11.7).

As we have seen, numerous effective policies exist to promote a faster transition to renewables. Many of these policies simply implement principles that we introduced early in this text—internalizing externalities through subsidizing positive externalities and taxing negative externalities. At a minimum, it makes economic sense to avoid perverse subsidies that increase external costs. In the next two chapters, we focus more specifically on the most pervasive and urgent externality associated with energy use—global climate change.

Box 11.7
IMPLICIT DISCOUNT RATES AND ENERGY EFFICIENCY

A major problem in increasing energy efficiency of appliances arises from high implicit discount rates. Suppose that a consumer can purchase a standard refrigerator for \$500 or an energy-efficient model for \$800. The energy efficient model will save the consumer \$15 per month in energy costs. From an economic point of view, we can say that the return on the extra \$300 invested in the efficient model is \$15 × 12 = \$180 per year, or 60 percent. Thus in less than two years, the consumer will actually come out ahead by buying the more efficient refrigerator.

Anyone offered a market investment that would have a guaranteed 60 percent annual return would consider this a tremendous opportunity. But it is likely that the refrigerator buyer will turn down the chance to make this fantastic return. The reason is that he or she will weigh more heavily the immediate decision to spend \$500 versus \$800 and therefore choose the cheaper model. We could say that the consumer is implicitly using a discount rate of greater than 60 percent to make this judgment—a consumer behavior that is difficult to justify economically, yet very common.

Summary

Energy is a fundamental input for economic systems. Current economic activity depends overwhelmingly on fossil fuels, including oil, coal, and natural gas. These fuels are nonrenewable. Renewable sources such as hydroelectric, wind, and solar power currently provide less than 10 percent of global energy.

World energy use has expanded rapidly and is projected to continue growing, with an increase in energy demand of 44 percent by 2040 in a "business-as-usual" scenario. While a continued heavy reliance on fossil fuels is projected under a business-as-usual scenario, the potential exists to reduce demand growth through energy efficiency, and to obtain a much larger proportion of global energy from renewables, over the next several decades.

Considering only market costs, fossil fuels tend to be cheaper than renewables. But this is misleading, since fossil fuels receive a disproportionate share of energy subsidies and current energy costs fail to account for negative externalities. If the price of different energy sources reflected their full social costs, then several renewables would gain a competitive advantage over fossil fuels. Also, the price of renewables is declining and relatively predictable, while the projected prices of fossil fuels are expected to rise and are highly uncertain. Thus even without internalizing externalities, renewables are becoming cost competitive with fossil fuels, and the largest proportion of new energy capacity is projected to be provided by renewables over the next 25 years.

The speed of the transition to renewable energy will be highly influenced by policy choices. Reforming fossil-fuel subsidies and instituting Pigovian taxes are two policies that can yield more economically efficient outcomes. Other potential policies include increasing energy research and development expenditures, feed-in tariffs, and renewable energy targets. Finally, the most cost-effective approach to address energy demand is to promote energy efficiency, which can limit demand growth in the developing world and reduce total energy demand in currently developed countries.

Key Terms and Concepts

biomass
capital stock
depletion allowances
economic efficiency standards
efficiency labeling
energy demand-side management
energy infrastructure
energy subsidies
energy transition
feed-in tariffs
Hubbert curve
hydropower
levelized costs
nonrenewable stock
present value
renewable energy targets
renewable flow
solar energy

Discussion Questions

1. Since energy production represents only about 8–10 percent of economic output, why should any special importance be placed on this sector? Is there any significant difference between an economic system that relies on nonrenewable energy supplies and one that uses primarily renewable sources? Should policy decisions about energy use be implemented by governments, or should the patterns of energy use be determined solely by market allocation and pricing?
2. How will the world's energy needs change over the coming decades? What are the different possibilities for energy development paths, and what are the advantages and drawbacks of different possible paths? Are we likely to run out of fossil fuels, or to shift away from fossil fuels for other reasons?
3. What policies are most relevant to promoting a transition to renewables? Is this likely to occur through the market, or are aggressive government polices required? What are the justifications for such policies from the point of view of environmental economics?

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4. See, for example, Hall and Klitgaard, 2012.
5. Morton, 2006.
6. International Energy Agency, 2015b.
7. BP Statistical Review of World Energy, 2012-2016; International Energy Agency, 2015c; U.S. Energy Information Administration, 2016a.
8. For detailed discussion of global climate analysis and policy, see Chapters 12 and 13.

9. U.S. EIA, 2015a.
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11. IEA, 2011, Executive Summary, 3.
12. Natural Gas Supply Association, naturalgas.org.
13. U.S. Energy Information Administration (EIA), 2011a.
14. See Howarth *et al.*, 2011; Wigley, 2011.
15. British Petroleum, 2016.
16. Clean Air Task Force, 2010.
17. British Petroleum, 2016.
18. Jacobson and Delucchi, 2011a, p. 1154.
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21. Jacobson and Delucchi, 2011b.
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Web Sites

1. **www.eia.gov.** Web site of the Energy Information Administration, a division of the U.S. Department of Energy that provides a wealth of information about energy demand, supply, trends, and prices.
2. **www.nrel.gov.** The web site of the National Renewable Energy Laboratory in Colorado. The NREL conducts research on renewable energy technologies including solar, wind, biomass, and fuel cell energy.
3. **www.rmi.org.** Homepage of the Rocky Mountain Institute, a nonprofit organization that "fosters the efficient and restorative use of resources to create a more secure, prosperous, and life-sustaining world." The RMI's main focus has been promoting increased energy efficiency in industry and households.
4. **www.eren.doe.gov.** Web site of the Energy Efficiency and Renewable Energy Network in the U.S. Department of Energy. The site includes a large amount of information on energy efficiency and renewable energy sources as well as hundreds of publications.
5. **www.iea.org.** Web site of the International Energy Agency, an "autonomous organisation which works to ensure reliable, affordable and clean energy for its 28 member countries and beyond." While some data are available only to subscribers, other data are available for free, as well as access to informative publications such as the "Key World Energy Statistics" annual report.
6. **www.energystar.gov.** Web site of the Energy Star program, including information about which products meet guidelines for energy efficiency.

CHAPTER

12

Global Climate Change: Science and Economics

Contributing author Anne-Marie Codur

Chapter 12 Focus Questions

- What are the impacts of global warming/global climate change?
- What consequences can we expect in the future?
- Can economic theory help evaluate the impact of climate change?
- How can we model the long-term impacts of climate change?

12.1 CAUSES AND CONSEQUENCES OF CLIMATE CHANGE

Scientists have been aware since the nineteenth century of the planetary impacts of carbon dioxide (CO_2) and other **greenhouse gases** in the atmosphere. In recent decades, concern has grown over the issue of **global climate change** caused by increased accumulations of these gases. (The problem often referred to as **global warming** is more accurately called global climate change. A basic warming effect will produce complex effects on climate patterns—with warming in some areas, cooling in others, and increased climatic variability and extreme weather events.) The horizon of projections for major consequences of climate change has become closer as scientific understanding of the physical processes has increased in recent years. What appeared ten years ago as a future threat for generations to come, in the late twenty-first century and beyond, is increasingly understood as an immediate and urgent issue, as many countries are already experiencing some of the disruptive consequences of climate change (see Box 12.1).

> **global climate change** the changes in global climate, including temperature, precipitation, storm frequency and intensity, and changes in carbon and water cycles, that result from increased concentrations of greenhouse gases in the atmosphere.
>
> **global warming** the increase in average global temperature as a result of emissions from human activities.
>
> **greenhouse gases** gases such as carbon dioxide and methane whose atmospheric concentrations influence global climate by trapping solar radiation.

Multiple studies published in peer-reviewed scientific journals show that 97 percent or more of actively publishing climate scientists agree: climate-warming trends over the past century are extremely likely to be due to human activities.[1] The 2013 and 2014 reports of the Intergovernmental Panel on Climate Change clearly attribute the majority of recently observed global climate change to human-made greenhouse gas emissions. The IPCC projects a temperature increase by 2100 of between 1.5°C (2.7°F) and 4.8°C (8.6°F), relative to pre-industrial levels.[2]

Recent statements by the U.S. Global Research Program and the American Geophysical Union indicate the widespread scientific acceptance of the reality of climate change, and the human role in its recent pattern:

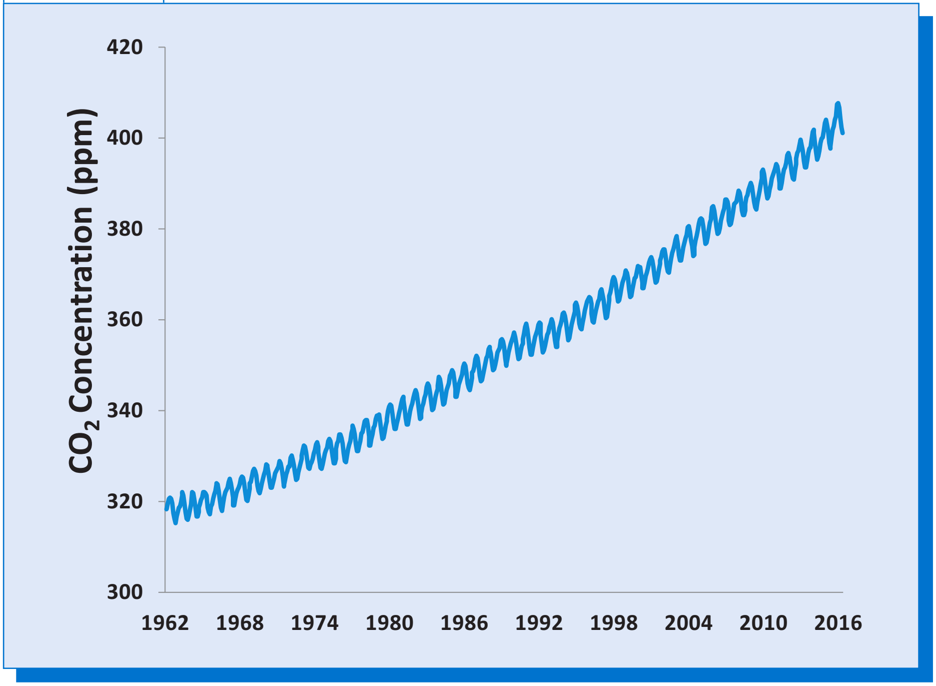
> Evidence for climate change abounds, from the top of the atmosphere to the depth of the oceans. Scientists and engineers from around the world have meticulously collected this evidence, using satellites and networks of weather balloons, observing and measuring changes in location and behaviors of species and functioning of ecosystems. Taken together, this evidence tells an unambiguous story: the planet is warming, and over the half century, this warming has been driven primarily by human activity.[3]
>
> Humanity is the major influence on the global climate change observed over the past 50 years. Rapid societal responses can significantly lessen negative outcomes.[4]

Putting climate change in the framework of economic analysis, we can consider greenhouse gas emissions, which cause planetary warming and other changes in weather patterns, as both a cause of environmental externalities and a case of the overuse of a **common property resource**.

> **common property resource** a resource that is available to everyone (nonexcludable), but use of the resource may diminish the quantity or quality available to others (rival).

The atmosphere is a **global commons** into which individuals and firms can release pollution. Global pollution creates a "public bad" affecting everyone—a negative externality with a wide impact.

Figure 12.1 Atmospheric Carbon Dioxide Levels



Source: National Oceanic and Atmospheric Administration, Earth System Research laboratory, Global Monitoring Division, http://www.esrl.noaa.gov/gmd/ccgg/trends/data.html.

Note: ppm = parts per million. Seasonal variations mean that CO_2 concentrations rise and fall each year with growth and decay of vegetation and other biological systems, but the long-term trend is a steady upward increase due to human emissions of CO_2.

Many countries have environmental protection laws limiting the release of local and regional air pollutants. In economic terminology, such laws to some degree internalize externalities associated with local and regional pollutants. But until relatively recently, few controls existed for carbon dioxide (CO_2), the major greenhouse gas, and concentrations of CO_2 in the atmosphere have risen steadily, recently crossing the benchmark of 400 parts per million (ppm) atmospheric concentration (Figure 12.1).

Impacts of climate change have already begun to affect climate patterns (see Box 12.1). If indeed the effects of climate change are likely to be severe, it is in everyone's interest to lower emissions for the common good. Climate change can thus be viewed as a **public good** issue, requiring collaborative action to develop adequate policies, as noted in Chapter 4. In the case of climate change, such action needs to involve all stakeholders, including governments and public institutions as well as private corporations and individual citizens.

After decades of failures at the international level to produce an agreement including all countries, significant progress was achieved in Paris in December 2015, when 195 nations, under the auspices of the United Nations Framework Convention on Climate Change, signed the first global agreement aiming at keeping the overall increase in global average temperature under 2°C

global commons global common property resources such as the atmosphere and the oceans.

public goods goods that are available to all (nonexclusive) and whose use by one person does not reduce their availability to others (nonrival).

(compared with pre-industrial times). In addition to the actions taken by national governments, hundreds of cities, regions, and corporations have pledged to make significant reductions in their CO_2 emissions over the next five to 25 years, although non-cooperation by the United States under the Trump administration may throw the success of the agreement into doubt. We will return to a detailed analysis of the Paris Agreement in Chapter 13.

greenhouse effect the effect of certain gases in the earth's atmosphere trapping solar radiation, resulting in an increase in global temperatures and other climatic impacts.

Box 12.1
WHAT IS THE GREENHOUSE EFFECT?

The sun's rays travel through a greenhouse's glass to warm the air inside, but the glass acts as a barrier to the escape of heat. Thus plants that require warm weather can be grown in cold climates. The global greenhouse effect, in which the earth's atmosphere acts like the glass in a greenhouse, was first described by French scientist Jean Baptiste Fourier in 1824.

Clouds, water vapor, and the natural greenhouse gases carbon dioxide (CO_2), methane, nitrous oxide, and ozone allow inbound solar radiation to pass through but serve as a barrier to outgoing infrared heat. This creates the natural **greenhouse effect**, which makes the planet suitable for life. Without it, the average surface temperature on the planet would average around -18°C (0°F), instead of approximately 15°C (60° F).

"The possibility of an *enhanced* or *man-made* greenhouse effect was introduced by the Swedish scientist Svante Arrhenius in 1896. Arrhenius hypothesized that the increased burning of coal, which had paralleled the process of industrialization, would lead to an increased concentration of carbon dioxide in the atmosphere and warm the earth" (Fankhauser, 1995). Since Arrhenius's time, the emissions of greenhouse gases have grown dramatically. CO_2 concentrations in the atmosphere have increased by 40 percent over pre-industrial levels (see Figure 12.1). In addition to increased burning of fossil fuels such as coal, oil, and natural gas, manmade chemical substances such as chlorofluorocarbons (CFCs) as well as methane and nitrous oxide emissions from agriculture and industry contribute to the greenhouse effect.

Scientists have developed complex computer models that estimate the effect of current and future greenhouse gas emissions on the global climate. While considerable uncertainty remains in these models, a broad scientific consensus has formed that the human-induced greenhouse effect poses a significant threat to the global ecosystem. The global average temperature increased by about 0.7°C (1.3°F) during the twentieth century. The Intergovernmental Panel on Climate Change (IPCC) has concluded in all its reports and especially in the most recent one, in 2014, that the global atmospheric concentrations of greenhouse gas (GHG) emissions have increased markedly as a result of human activities since 1750. According to the report, "Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history . . . Warming of the climate system is unequivocal, and since the 1950s many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen." The IPCC projected a global average temperature increase by 2100 of between 1.5°C and 4.8°C, (between 2.7°F and 8.6°F) above pre-industrial levels. By 2015, the world had already reached an average increase of temperatures of 1°C compared with pre-industrial times.

Sources: Fankhauser 1995; IPCC, 2014a, b, and c; Damian Carrington, "World's Climate About to Enter 'Uncharted Territory' as it Passes 1°C of Warming," *The Guardian*, 9 November, 2015.

Because CO_2 and other greenhouse gases continuously accumulate in the atmosphere, stabilizing or "freezing" emissions will not solve the problem. Greenhouse gases persist in the atmosphere for decades or even centuries, continuing to affect the climate of the entire planet long after they are emitted. This is a case of a **cumulative or stock pollutant**. As discussed in Chapter 8, only major reductions in emissions levels of a stock pollutant will prevent ever-increasing atmospheric accumulations. Development of national and international policies to combat global climate change is a huge challenge, involving many scientific, economic, and social issues. In this chapter we address the issues of analysis of climate change, using techniques and concepts developed in earlier chapters, and in Chapter 13 we turn to policy implications.

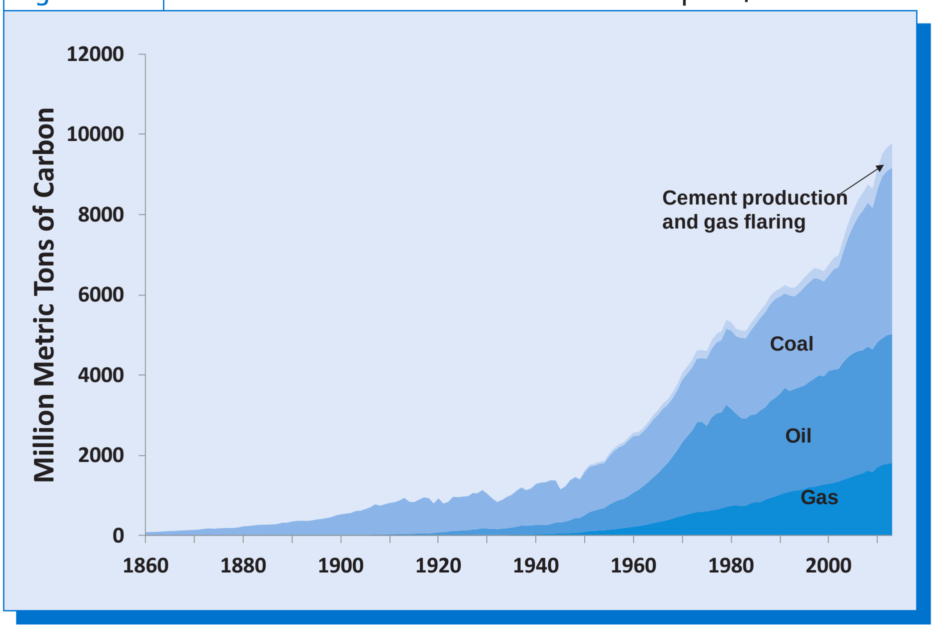
cumulative or stock pollutant a pollutant that does not dissipate or degrade significantly over time and can accumulate in the environment, such as carbon dioxide and chlorofluorocarbons.

Trends in Global Carbon Emissions

Global emissions of CO_2 from the combustion of fossil fuels have increased dramatically since about 1950, as illustrated in Figure 12.2. In 2013 total global carbon emissions were 9.776 billion tons or Gigatons (Gt) of carbon. Coal burning is currently responsible for about 42 percent of global carbon emissions, while liquid fuels (primarily oil) are the source of another 33 percent, combustion of natural gas accounts for 19 percent, with 6 percent from cement production and gas flaring.[5] Figure 12.2 shows emissions over the period 1965–2015, expressed in million metric tons of carbon.

Figure 12.3 focuses on the distribution of emissions between two groups of countries: the OECD, including primarily industrialized countries; and the rest of the world, comprising

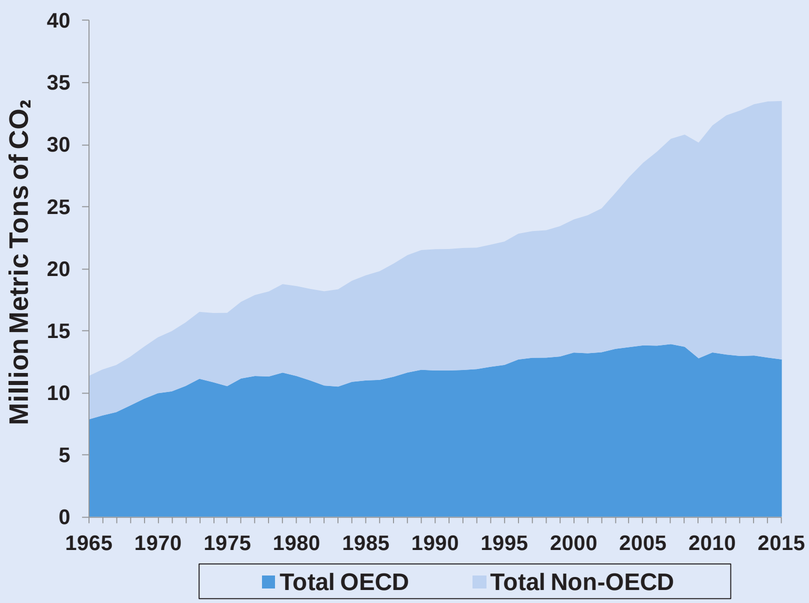
Figure 12.2 Carbon Emissions from Fossil Fuel Consumption, 1860–2013



Source: Carbon Dioxide Information Analysis Center (CDIAC), http://cdiac.ornl.gov/ftp/ndp030/global.1751_2013.ems, accessed June 2016.

Note: Emissions in million metric tons (MMt) of carbon.

Figure 12.3 **Carbon Dioxide Emissions, 1965–2015, Industrialized and Developing Countries** (Million Metric Tons of CO_2)



Source: U.S. Energy Information Administration, http://www.eia.gov/forecasts/aeo/data/browser/#/?id=10-IEO2016&sourcekey=0, accessed June 2016.

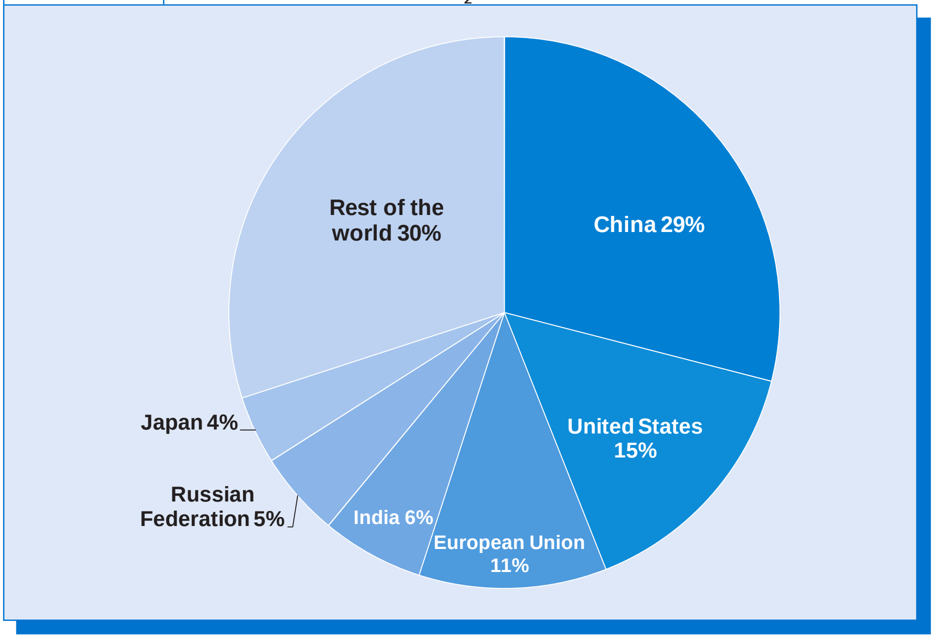
Note: OECD = Organization for Economic Cooperation and Development (primarily industrialized countries, while non-OECD are developing countries). The vertical axis in Figure 12.3 measures million metric tons of carbon dioxide. (The weight of a given amount of emissions measured in tons of carbon dioxide is about 3.67 times the total weight in carbon. The atomic weight of carbon is 12 atomic mass units, while the weight of carbon dioxide is 44. Thus one ton of carbon is equivalent to 44/12 = 3.67 tons of carbon dioxide.) The emissions estimates of the U.S. EIA shown here differ slightly from those of the CDIAC shown in Figure 12.2.

developing countries and including China. The share of emissions attributable to the OECD countries has been steadily declining since 2007, and the share of the developing world has increased significantly, though there has also been a recent slowdown in its growth. (Figure 12.3 shows emissions in million metric tons of carbon dioxide, rather than carbon as in Figure 12.2. See explanatory note below Figure 12.3.)

Emissions are closely connected with the economic cycles, and the 2008–2009 recession is clearly visible on the graph. Also noteworthy is the apparent leveling off of CO_2 emissions in the years 2014 and 2015, around the figure of 33 billion tons (33 gigatons) of CO_2, a trend that has continued in 2016. This is partly explained by a slowing down of global economic growth (with a decrease in China's economic growth rate). It also reflects new energy investments in renewables (solar and wind), which as noted in Chapter 11 have dominated additional energy production capacity in recent years. In developed countries, there has been a rapid switch from coal to natural gas and renewable energy, lowering overall CO_2 emissions. In developing countries, coal production is still expanding, but an increasing share of new energy production is also coming from renewables.[6]

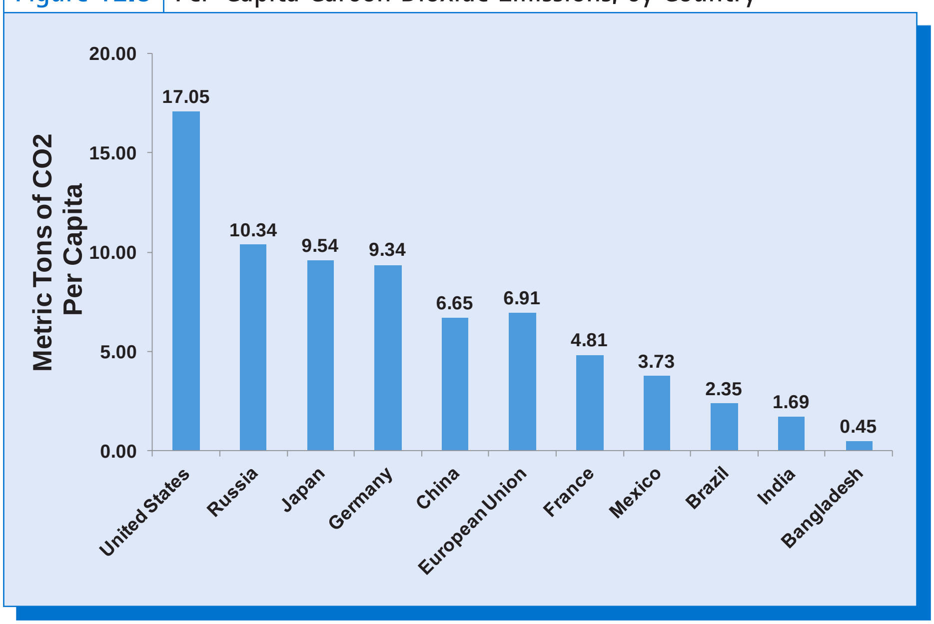
business as usual a scenario in which no significant policy, technology, or behavioral changes are expected.

Figure 12.4 Percentage of Global CO_2 Emissions by Country/Region.



Source: Olivier *et al.*, 2014.

Figure 12.5 Per-Capita Carbon Dioxide Emissions, by Country



Source: Source: British Petroleum, 2015, energy charting tool.

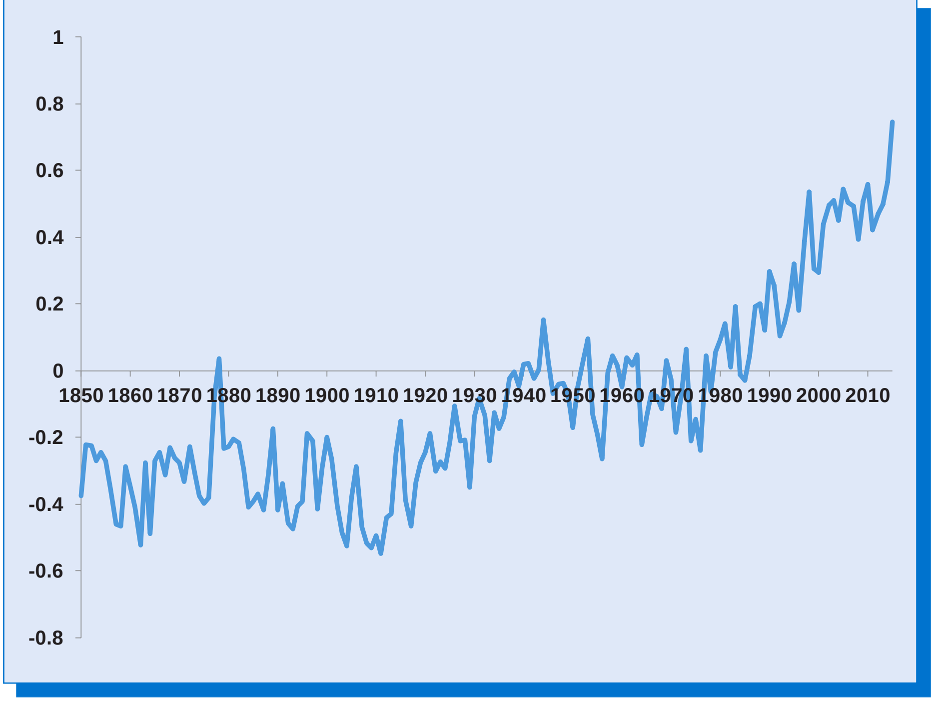
Figure 12.4 shows the distribution of CO_2 emissions among the main emitters: China (29 percent), the United States (15 percent), the European Union (11 percent), India (6 percent), Russia (5 percent), Japan (4 percent), and the rest of the world (30 percent). Most of the future growth in carbon emissions is expected to come from rapidly expanding developing countries such as China and India. China surpassed the United States in 2006 as the largest carbon emitter in the world.

In addition to total emissions by country, it is important to consider per capita emissions. Per capita emissions are much higher in developed countries, as shown in Figure 12.5. The United States has the highest rate among major countries, with 17 metric tons of CO_2 emissions per person, followed by Russia with an average of 10 tons per person, while other developed countries are in the range of 4 to 10 metric tons per capita. Most developing countries have low rates per capita, typically less than 4 tons of CO_2 per person, except China, whose per capita emissions have grown to 6.6 tons per person.

Trends and Projections for Global Climate

The earth has warmed significantly since reliable weather records began to be kept in the mid-nineteenth century (Figure 12.6). In the past 100 years the global average temperature has risen about 1°C, or about 1.8°F. Fourteen of the 15 warmest years in the modern meteorological record have occurred between 2000 and 2015.[7] The record of 2014 as the hottest year ever recorded was broken by the year 2015, and as this text went to press, the year 2016 was on track to be even hotter than 2015. According to the World Meteorological Association, "It is very likely that 2016 will be the hottest year on record, with global temperatures even higher than the record-breaking temperatures in 2015."[8] Evidence indicates that the rate of

Figure 12.6 Global Annual Temperature Anomalies (°C), 1850–2015



Source: CDIAC, Global Monthly and Annual Temperature Anomalies (°C), 1850–2015, relative to the 1961–1990 mean, May 2016, http://cdiac.ornl.gov/ftp/trends/temp/jonescru/global.txt.

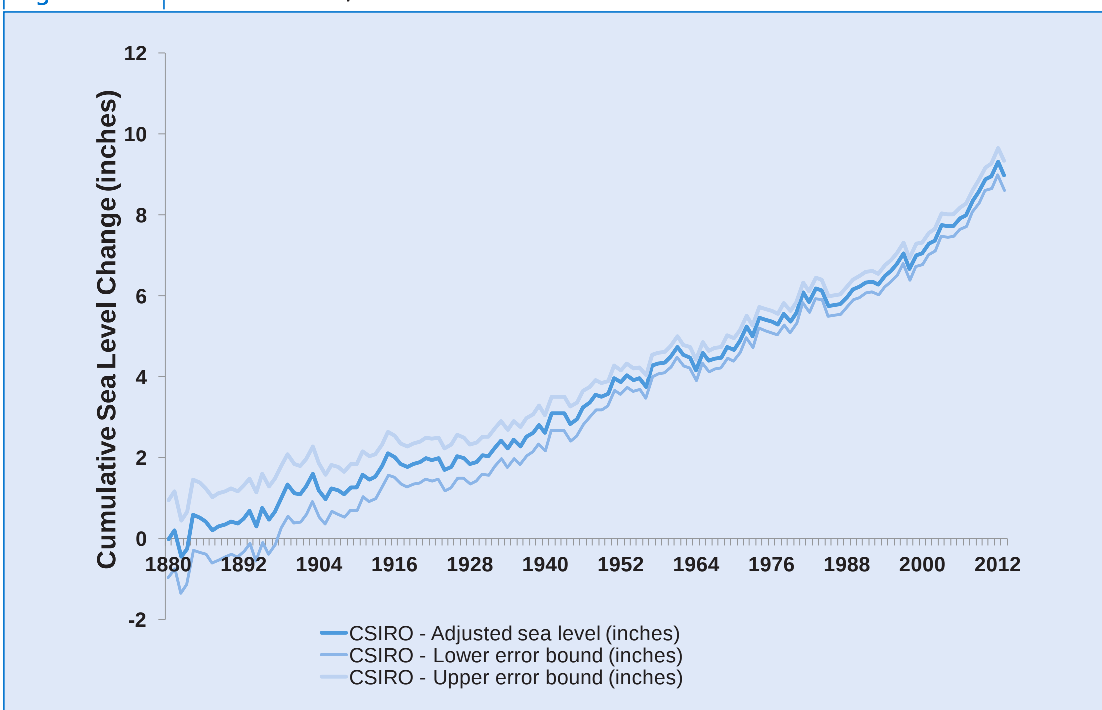
Note: The zero baseline represents the average global temperature from 1961 to 1990.

warming, currently about 0.13°C per decade, is increasing. A study by the U.S. Department of Energy's Pacific Northwest National Laboratory shows that the rate at which temperatures are rising could be 0.25°C per decade by 2020.[9] Not all areas are warming equally. The Arctic and Antarctic regions have been warming at about double the global rate.[10]

Warmer temperatures have produced noticeable effects on ecosystems. In most regions of the world, glaciers are retreating. For example, Glacier National Park in Montana had 150 glaciers when the park was established in 1910. As of 2010 only 25 glaciers remained, and by 2030 it is estimated that the park will no longer have any of its namesake glaciers. Climate change is also leading to rising sea levels. Sea-level rise is attributed to the melting of glaciers and ice sheets and to the fact that water expands when it is heated. In 2012 the global average ocean temperature was about 0.5°C above the twentieth-century average. The combination of warmer oceans and melting ice has led sea levels to rise about 2 millimeters per year, and in 2012 the sea level was already 9 inches (23 cm) above the level of 1880 (see Figure 12.7 and Box 12.2).[11] The impact of rising seas threatens numerous coastal areas; for example, the U.S. government has identified 31 Alaskan towns and cities at imminent risk, and cities in Florida are already experiencing significant damage from a major increase in flooding.[12]

Recent research on the West Antarctic ice sheet shows that this area, larger than Mexico, is potentially vulnerable to disintegration from a relatively small amount of global warming, and capable of raising the sea level by 12 feet or more should it happen. Even without disintegration of the West Antarctic ice sheet, researchers found that the total sea rise could

Figure 12.7 Sea-Level Rise, 1880–2012



Source: IPCC, 2014a.

Note: The line in the middle shows an average estimate based on a large number of data sources. The upper and lower lines represent the high level and low level margins of error (smaller for recent data).

Box 12.2
PACIFIC ISLANDS DISAPPEAR AS OCEANS RISE

The island nation of Kiribati, a collection of 33 coral atolls and reef islands, lying no higher than 6 feet above sea level, scattered across a swath of the Pacific Ocean about twice the size of Alaska, is facing the risk of going under in the next few decades.

Two of its islands, Tebua Tarawa and Abanuea, have already disappeared as a result of rising sea level. Others, both in Kiribati and in the neighboring island country of Tuvalu, are nearly gone. So far the seas have completely engulfed only uninhabited, relatively small islands, but the crisis is growing all around the shores of the world's atolls.

Populated islands are already suffering. The main islands of Kiribati, Tuvalu, and the Marshall Islands (also in the Pacific) have suffered severe floods as high tides demolish sea walls, bridges and roads, and swamp homes and plantations. Almost the entire coastline of the 29 Marshall Islands atolls is eroding. World War II graves on its main Majuro atoll are washing away, roads and subsoils have been swept into the sea, and the airport has been flooded several times despite the supposed protection of a high sea wall.

The people of Tuvalu are finding it difficult to grow their crops because the rising seas are poisoning the soil with salt. Many islands will become uninhabitable long before they physically disappear, as salt from the sea contaminates the underground freshwater supplies on which they depend. In both Kiribati and the Marshall Islands families are desperately trying to keep the waves at bay by dumping trucks, cars, and other old machinery in the sea and surrounding them with rocks. The situation is so bad that the leaders of Kiribati are considering a plan to move the entire population of 110,000 to Fiji. The inhabitants of some villages have already moved.

Sources: Mike Ives, "A Remote Pacific Nation, Threatened by Rising Seas," *New York Times*, July 2, 2016; "Kiribati Global Warming Fears: Entire Nation May Move to Fiji," Associated Press, March 12, 2012.

reach five to six feet by 2100, and would continue to increase, with the seas rising by more than a foot per decade by the middle of the twenty-second century.[13]

In addition to rising ocean temperatures, increased CO_2 in the atmosphere results in **ocean acidification**. According to the U.S. National Oceanic and Atmospheric Administration, "around half of all carbon dioxide produced by humans since the Industrial Revolution has dissolved into the world's oceans. This absorption slows down global warming, but it also lowers the oceans pH, making it more acidic. More acidic water can corrode minerals that many marine creatures rely on to build their protective shells and skeletons."[14]

> **ocean acidification** increasing acidity of ocean waters as a result of dissolved carbon from CO_2 emitted into the atmosphere.

A 2012 report in *Science* magazine found that the oceans are turning acidic at what may be the fastest pace in 300 million years, with potential severe consequences for marine ecosystems.[15] Among the first victims of ocean warming and acidification are coral reefs, because corals can form only within a narrow range of temperatures and acidity of seawater. The year 2015 saw a record die-off of coral reefs, known as coral bleaching, due to a combination of the most powerful El Niño (Pacific warming) climate cycle in a century and water temperatures already elevated due to climate change.[16] Oyster hatcheries, which have been referred to as "canaries in a coal mine" since they may predict effects on a wide range of ocean ecosystems as ocean acidification increases, are also affected, threatening the Pacific Northwest shellfish industry.[17] Other ecosystems are also severely impacted by climate change (see Box 12.3).

Box 12.3
FORESTS, CLIMATE CHANGE, AND WILDFIRES

Wildfires were once primarily a seasonal threat, taking place mainly in hot, dry summers. Now they are burning nearly year-round in the Western United States, Canada, and Australia. In May 2016, the state of Alberta was devastated by wildfires expanding over 350 miles, leading to the evacuation of the 80,000 inhabitants of the city of Fort McMurray, which suffered extensive damage.

Global warming is suspected as a prime cause of the increase in wildfires. The warming is hitting northern regions especially hard: temperatures are climbing faster there than for the Earth as a whole, snow cover is melting prematurely, and forests are drying out earlier than in the past. Dry winters mean less moisture on the land, and the excess heat may even be causing an increase in lightning, which often sets off the most devastating wildfires.

According to a research ecologist for the United States Forest Service: "In some areas, we now have year-round fire seasons, and you can say it couldn't get worse than that. But we expect from the changes that it can get worse." The United States Forest Service spent more than half of its budget on firefighting in 2015, at the expense of programs such as controlled burning aimed at reducing the risk of fires. Scientists see a risk that if the destruction of forests from fires and insects keeps rising, the carbon that has been locked away in the forests will return to the atmosphere as carbon dioxide, accelerating the pace of global warming—a dangerous feedback loop.

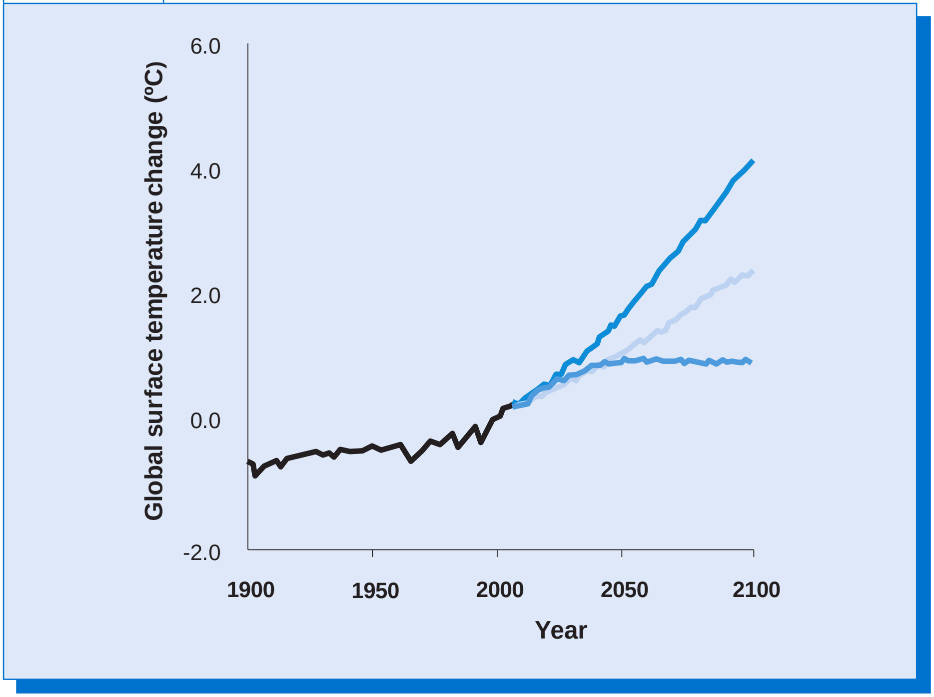
Sources: Matt Richtel and Fernanda Santos, "Wildfires, Once Confined to a Season, Burn Earlier and Longer," *New York Times*, April 12, 2016; Ian Austen, "Wildfire Empties Fort McMurray in Alberta's Oil Sands Region," *New York Times*, May 3, 2016, http://www.fs.fed.us/sites/default/files/2015-Fire-Budget-Report.pdf.

Future projections of climate change depend on the path of future emissions. Even if all emissions of greenhouse gases ended today, the world would continue warming for many decades, and effects such as sea-level rise would continue for centuries, because the ultimate environmental effects of emissions are not realized immediately.[18] Based on a wide range of models with different assumptions about future emissions, the IPCC estimated in its 2014 report that during the twenty-first century global average temperatures will rise within a range most likely to be between 1.5°C (3°F) and 4.8°C (8.6°F) above pre-industrial levels, unless drastic policy action to reduce emissions occurs.[19] Expected temperature increases for high-, medium-, and low-emissions scenarios are shown in Figure 12.8.

The magnitude of actual warming and other effects will depend upon the level at which atmospheric concentrations of CO_2 and other greenhouse gases are ultimately stabilized. Pre-industrial levels of concentration were around 280 parts per million (ppm). A 2008 scientific paper by climate scientists James Hansen and Rajandra Pachauri, the chairperson of the IPCC, declared that: "If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that CO_2 will need to be 350 ppm."[20] In 2015, the atmospheric CO_2 concentration passed the milestone of 400 ppm.[21] When we also include the contribution of other greenhouse gases, the overall effect is equivalent to a concentration of 430 ppm of CO_2 or more, referred to as **CO_2 equivalent (CO_2e)**. This level of CO_2 equivalent has not been experienced for over 800,000 years.[22]

CO_2 equivalent (CO_2e) a measure of total greenhouse gas emissions or concentrations, converting all non-CO_2 gases to their CO_2 equivalent in warming impact.

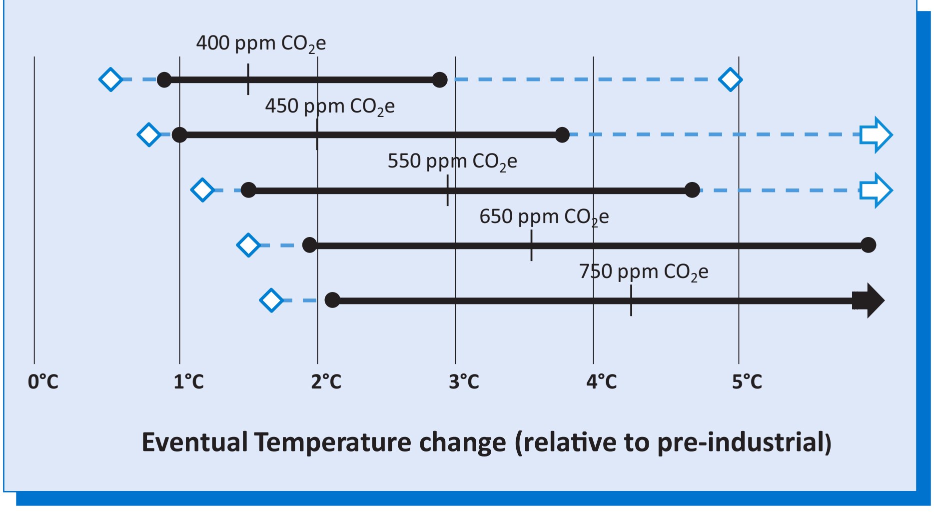
Figure 12.8 Global Temperature Trends, 1900–2100



Source: IPCC 2014a, p. 1037.

Note: The graph shows mean projections for high-, medium-, and low-emissions scenarios. The possible range of temperature increases in all IPCC models is wider, ranging between 0.3 and 4.8°C.

Figure 12.9 Relationship Between Level of Greenhouse Gas Stabilization and Eventual Temperature Change



Source: Stern, 2007.

Note: CO_2e = CO_2 equivalent; ppm = parts per million.

Figure 12.9 relates the stabilization level of greenhouse gases, measured in CO_2e, to the resulting rise in global average temperatures, incorporating the degree of uncertainty. The solid bar at each level of CO_2e represents a range of temperature outcomes that is likely to occur with a 90 percent probability. The dashed line extending beyond this interval at either end represents the full range of predicted results from the major existing climate models. The vertical line around the middle of each bar represents the midpoint of the different predictions.

This projection suggests that stabilizing greenhouse gas concentrations at 450 ppm CO_2e would be 90 percent likely to eventually result in a temperature increase between 1.0 and 3.8°C, with a small probability that the rise could be significantly more than this. With current greenhouse gas concentrations in the atmosphere at over 430 ppm CO_2e, stabilization at 450 ppm is likely impossible to achieve without significant withdrawal of CO_2 from the atmosphere—implying net emissions below zero at some point in the future. Even stabilization at 550 ppm CO_2e would require strong and immediate policy action (discussed further in Chapter 13).

12.2 RESPONSES TO GLOBAL CLIMATE CHANGE

The onset of climate change demands both **preventive strategies** and **adaptive strategies**. Consider, for example, the damage caused by rising sea levels. The only way to stop this would be to prevent climate change entirely—something that is now impossible. It might be possible in some cases to build dikes and sea walls to hold back the higher waters. Those who live close to the sea—including whole island nations that could lose most of their territory to sea-level rise—will suffer major costs under any adaptation strategy. But a prevention strategy that could slow, though not stop, sea-level rise requires convincing most of the world's countries to participate. The Paris Agreement of 2015 represented a step toward realization, on the part of the 195 signatory countries, that there was a common interest in combatting climate change. But even if significant action does come from global agreements, adaptation costs will still be very large.

preventive measures/preventive strategies actions designed to reduce the extent of climate change by reducing projected emissions of greenhouse gases.

adaptive measures/adaptive strategies actions designed to reduce the magnitude or risk of damages from global climate change.

Scientists have modeled the results of a projected doubling of accumulated carbon dioxide in the earth's atmosphere. Some of the predicted effects are:

- Loss of land area, including beaches and wetlands, because of sea-level rise
- Loss of species and forest area
- Disruption of water supplies to cities and agriculture
- Increased air conditioning costs
- Health damage and deaths from heat waves and spread of tropical diseases
- Loss of agricultural output due to drought

Beneficial outcomes might include:

- Increased agricultural production in cold climates
- Lower heating costs
- Fewer deaths from exposure to cold

The potentially beneficial outcomes would be experienced primarily in northern parts of the Northern hemisphere, such as Iceland, Siberia, and Canada. Most of the rest of the world, especially tropical and semi-tropical areas, are likely to experience strongly negative effects from additional warming.

In addition, other less-predictable but possibly more damaging and permanent effects include:

- Disruption of weather patterns, with increased frequency of hurricanes, droughts, and other extreme weather events.
- Sudden major climate changes, such as a shift in the Atlantic Gulf Stream, which could change the climate of Europe to that of Alaska.
- Positive **feedback effects**, such as an increased release of CO_2 from warming arctic tundra, which would speed up global warming. (A feedback effect occurs when an original change in a system causes further changes that either reinforce the original change (positive feedback) or counteract it (negative feedback)).

According to IPCC projections, with increasing emissions and higher temperatures, negative effects will intensify and positive effects diminish (Table 12.1). As shown in Figure 12.8, there is considerable uncertainty about the expected global warming in the next century. We need to keep such uncertainties in mind as we evaluate economic analyses of global climate change.

Given these uncertainties, some economists have attempted to place the analysis of global climate change in the context of **cost-benefit analysis**. Others have criticized this approach as an attempt to put a monetary valuation on issues with social, political, and ecological implications that go far beyond dollar value. We first examine economists' efforts to capture the impacts of global climate change through cost-benefit analysis and then return to the debate over how to assess potential greenhouse gas reduction policies.

feedback effect the process of changes in a system leading to other changes that either counteract or reinforce the original change.

cost-benefit analysis (CBA) a tool for policy analysis that attempts to monetize all the costs and benefits of a proposed action to determine the net benefit.

12.3 ECONOMIC ANALYSIS OF CLIMATE CHANGE

Without policy intervention, carbon emissions in a business-as-usual scenario would be expected to continue to rise as shown in Figure 12.10. These projections, however, are based on current trends without considering the impacts of future emissions reductions policies. Aggressive and immediate policy action is required first to stabilize and then to reduce total CO_2 emissions in the coming decades. This is the goal of the 2015 Paris Agreement. To understand the issues involved in reducing emissions, we need to look at the economic implications of such policy initiatives.

When economists perform a cost-benefit analysis, they weigh the consequences of the projected increase in carbon emissions versus the costs of current policy actions to stabilize or even reduce CO_2 emissions. Strong policy action to prevent climate change will bring benefits equal to the value of damages that are avoided. These benefits of preventing damage can also be referred to as **avoided costs**. The estimated benefits must then be compared to the costs of taking action. Various economic studies have attempted to estimate these benefits and costs.

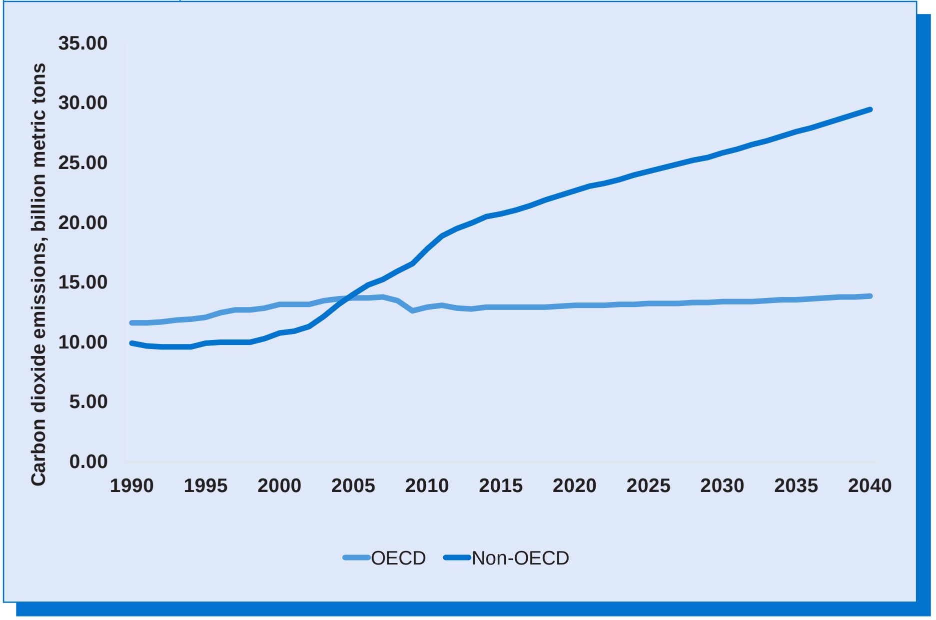
avoided costs costs that can be avoided through environmental preservation or improvement

Table 12.1 Possible Effects of Climate Change

Type of Impact	Eventual Temperature Rise Relative to Pre-Industrial Temperatures				
	1°C	2°C	3°C	4°C	5°C
Freshwater Supplies	Small glaciers in the Andes disappear, threatening water supplies for 50 million people	Potential water supply decrease of 20–30% in some regions (Southern Africa and Mediterranean)	Serious droughts in southern Europe every 10 years; 1–4 billion more people suffer water shortages	Potential water supply decrease of 30–50% in southern Africa and Mediterranean	Large glaciers in Himalayas possibly disappear, affecting 1/4 of China's population
Food and Agriculture	Modest increase in yields in temperate regions	Declines in crop yields in tropical regions (5–10% in Africa)	150–550 million more people at risk of hunger; yields likely to peak at higher latitudes	Yields decline by 15–35% in Africa; some entire regions out of agricultural production	Increase in ocean acidity, possibly reduces fish stocks
Human Health	At least 300,000 die each year from climate-related diseases; reduction in winter mortality in high latitudes	40–60 million more exposed to malaria in Africa	1–3 million more potentially people die annually from malnutrition	Up to 80 million more people exposed to malaria in Africa	Further disease increase and substantial burdens on health care services
Coastal Areas	Increased damage from coastal flooding	Up to 10 million more people exposed to coastal flooding	Up to 170 million more people exposed to coastal flooding	Up to 300 million more people exposed to coastal flooding	Sea-level rise threatens major cities such as New York, Tokyo, and London
Ecosystems	At least 10% of land species facing extinction; increased wildfire risk	15–40% of species potentially face extinction	20–50% of species potentially face extinction; possible onset of collapse of Amazon forest	Loss of half of Arctic tundra; widespread loss of coral reefs	Significant extinctions across the globe

Sources: IPCC, 2007b; Stern, 2007.

Figure 12.10 Energy-Related Carbon Dioxide Emissions, Projected to 2040



Source: EIA, 2016.

Note: The Organization for Economic Cooperation and Development (OECD) includes primarily industrialized countries, and non-OECD countries comprise the rest of the world, including developing countries and China.

Attempting to measure the costs of climate change in monetized terms, or as a percentage of GDP, poses several inherent problems. In general, these studies can only capture effects of climate change insofar as they impact economic production, or create non-market impacts that can be expressed in monetary terms (as discussed in Chapter 7). Some sectors of the economy are potentially vulnerable to the effects of climate change, including farming, forestry and fishing, coastal real estate, and transportation. But these compose only about 10 percent of GDP. Other major areas, such as manufacturing, services, and finance, are seen as only lightly affected by climate change.[23] Thus an estimate of GDP impacts may tend to omit some of the most powerful ecological effects of climate change. According to William Nordhaus, who has authored many cost-benefit studies of climate change over the past 20 years:

> [T]he most damaging aspects of climate change—in unmanaged and unmanageable human and natural systems—lie well outside the conventional marketplace. I identified four specific areas of special concern: sea-level rise, hurricane intensification, ocean acidification, and loss of biodiversity. For each of these the scale of the changes is at present beyond the capability of human efforts to stop. To this list we must add concerns about earth system singularities and tipping points, such as those involved in unstable ice sheets and reversing ocean currents. These impacts are not only hard to measure and quantify in economic terms; they are also hard to manage from an economic and engineering perspective. But to say that they are hard to quantify and control does not mean that they should be ignored. Quite the contrary, these systems are the ones that should be studied most carefully because they are likely to be the most dangerous over the longer run. [24]

Cost-benefit analysis, as discussed in Chapter 7, can also be controversial, since it puts a dollar figure on the value of human health and life. As noted in Chapter 7, most studies follow a common cost-benefit practice of assigning a value of about $8–11 million to a life, based on studies of the amounts that people are willing to pay to avoid life-threatening risks, or are willing to accept (e.g., in extra salary for dangerous jobs) to undertake such risks. But also as noted in Chapter 7, lower human life values tend to be assigned in developing nations, since the methodology for determining the value of a "statistical life" depends on monetary measures, such as incomes and contingent valuation. Since many of the most serious impacts of climate change will be experienced in developing nations, this economic valuation bias clearly raises both analytical and moral issues.

The issue of uncertainty, also discussed in Chapter 7, is central to cost-benefit analysis of climate change. Damage estimates tend to omit the possibility of the much more catastrophic consequences that *could* result if weather disruption is much worse than anticipated. A single hurricane, for example, can cause tens of billions in damage, in addition to loss of life. Hurricane Katrina in August 2005, for example, caused over $100 billion in damage, in addition to loss of over 1,800 lives. Hurricane Sandy, in 2012, caused about $50 billion in damages, disrupting power to nearly 5 million customers and leaving lasting effects on an extensive area of shoreline in New York and New Jersey. If climate change causes severe hurricanes to become much more frequent, cost-benefit analyses would have to estimate the costs of destruction at a much higher level than they have done previously. Another of the unknown values—human morbidity, or losses from disease—could well be enormous if tropical diseases extend their range significantly due to warmer weather conditions.

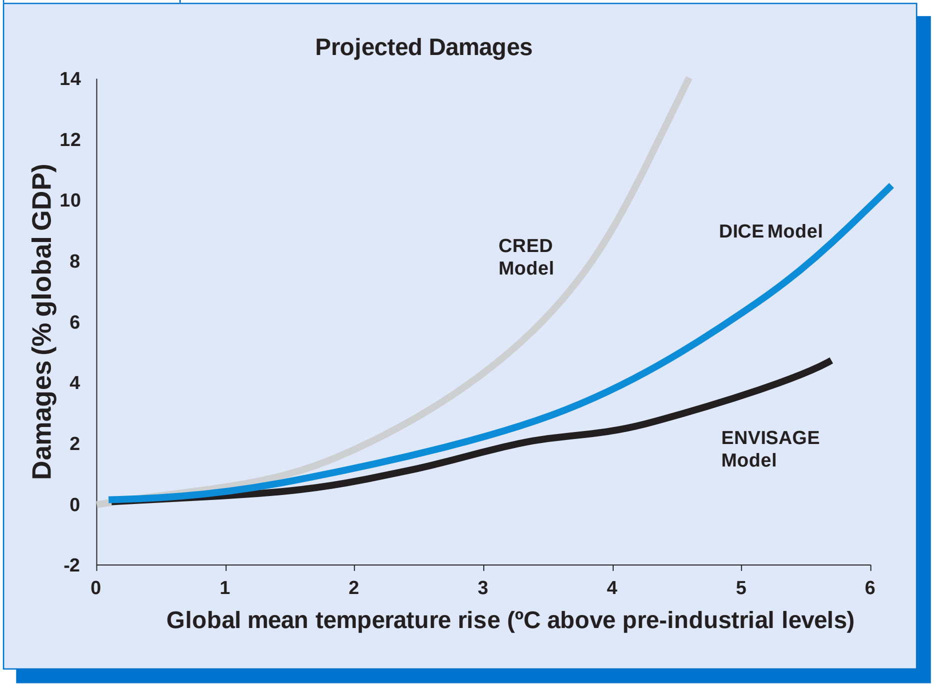
"Integrated assessment" models have been used by scientists and economists to translate scenarios of population and economic growth, and resulting emissions into changes in atmospheric composition and global mean temperature. These models then apply "damage functions" that approximate the global relationships between temperature changes and the economic costs from impacts such as changes in sea level, cyclone frequency, agricultural productivity, and ecosystem function. Finally, the models attempt to translate future damages into present monetary value.[25]

Higher ranges of temperature change lead to dramatically increased damage estimates at the global level, as shown in Figure 12.11. Different models yield different estimates for future damages and in turn different impacts on the economy, ranging from 2 percent to 10 percent or more of global GDP per year, depending on the global mean temperature rise. The values in Figure 12.11 show results from three widely used models with damage estimates based on the IPPC estimates of likely temperature change by 2100. These monetized estimates of damage may be subject to controversy and may not cover all aspects of damage, but suppose that we decide to accept them—at least as a rough estimate. We must then weigh the estimated benefits of policies to prevent climate change against the costs of such policies. To estimate these costs, economists use models that show how inputs such as labor, capital, and resources produce economic output.

marginal abatement costs costs of reduction for one extra unit of pollution, such as carbon emissions.

To lower carbon emissions, we must cut back the use of fossil fuels, substituting other energy sources that may be more expensive and investing in new infrastructure for renewables, energy efficiency, and other carbon abatement strategies. Economists calculate a measure of **marginal abatement costs**—the cost of reduction of one extra unit of carbon—for various measures, such as energy efficiency, shifting to solar and wind power, or avoided deforestation. Some of these measures are low cost, or even negative cost (meaning that they bring a net economic benefit in addition to their carbon-reducing contribution—more on this in the next chapter). But especially for very substantial carbon reduction, most economic models predict some negative impact on GDP. One summary of a broad array of studies, known as a

Figure 12.11 Increasing Damages from Rising Global Temperatures



Source: Revesz *et al*., 2014, http://www.nature.com/news/global-warming-improve-economic-models-of-climate-change-1.14991.

Note: The three different models (ENVISAGE, DICE, and CRED) shown in this figure give damage estimates that are similar at low to moderate levels of temperature change, but diverge at higher levels, reflecting different assumptions used in modeling.

meta-analysis, found that estimates of the impact on GDP vary based on assumptions about the possibilities for substitution of new energy sources, technological learning, and general economic flexibility.[26]

One estimate of the costs of meeting the Paris Agreement target of no more than 2°C temperature increase is that it would require about 1.5 percent of world income (about the equivalent of one year's growth in real income). But this is under best-case assumptions of international cooperation. Under less favorable assumptions, costs are estimated to rise to above 4 percent of global GDP.[27] Similarly, the meta-analysis referred to above finds that costs could vary from 3.4 percent of global GDP under worst-case assumptions to an *increase* in global GDP of 3.9 percent using best-case assumptions.[28]

If costs and benefits of an aggressive carbon abatement policy are both in the range of several percent of GDP, how can we decide what to do? Much depends on our evaluation of **future costs and benefits**. The costs of taking action must be borne today or in the near future. The benefits of taking action (the avoided costs of damages) are further in the future. Our task, then, is to decide today how to balance these future costs and benefits.

As we saw in Chapter 7, economists evaluate future costs and benefits by the use of a **discount rate**. The problems and implicit

future costs and benefits benefits and costs that are expected to occur in the future, usually compared to present costs through discounting.

discount rate the annual rate at which future benefits or costs are discounted relative to current benefits or costs.

value judgments associated with discounting add to the uncertainties that we have already noted in valuing costs and benefits. This suggests that we should consider some alternative approaches—including techniques that can incorporate the ecological as well as the economic costs and benefits.

Economic studies dealing with cost-benefit analysis of climate change have come to very different conclusions about policy. According to early studies (2000 to 2008) by William Nordhaus and colleagues, the "optimal" economic policies to slow climate change involve modest rates of emissions reductions in the near term, followed by increasing reductions in the medium and long term, sometimes referred to as a gradual "ramping up" of climate policy.[29]

Most early economic studies of climate change reached conclusions similar to those of the Nordhaus studies, although a few recommended more drastic action. The debate on climate change economics changed significantly in 2007, when Nicholas Stern, a former chief economist for the World Bank, released a 700-page report, sponsored by the British government, titled "The Stern Review on the Economics of Climate Change."[30] While most previous economic analyses of climate change suggested relatively modest policy responses, the Stern Review strongly recommended immediate and substantial policy action:

> The scientific evidence is now overwhelming: climate change is a serious global threat, and it demands an urgent global response. This Review has assessed a wide range of evidence on the impacts of climate change and on the economic costs, and has used a number of different techniques to assess costs and risks. From all these perspectives, the evidence gathered by the Review leads to a simple conclusion: the benefits of strong and early action far outweigh the economic costs of not acting.

Using the results from formal economic models, the Review estimates that if we don't act, the overall costs and risks of climate change will be equivalent to losing at least 5 percent of global GDP each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20 percent of GDP or more. In contrast, the costs of action—reducing greenhouse gas emissions to avoid the worst impacts of climate change—can be limited to around 1 percent of global GDP each year.[31] This benefit/cost ratio of at least 5:1 implies a strong economic case for immediate and major policy action, as opposed to a slower "ramping up."

What explains the difference between these two approaches to economic analysis of climate change? One major issue is the choice of the discount rate to use in valuing future costs and benefits.

As we saw in Chapter 7, the present value (PV) of a long-term stream of benefits or costs depends on the discount rate. A high discount rate will lead to a low present valuation for benefits that are mainly in the longer term, and a high present valuation for short-term costs. In contrast, a low discount rate will lead to a higher present valuation for longer-term benefits. The estimated net present value of an aggressive abatement policy will thus be much higher if we choose a low discount rate.

While both the Stern and Nordhaus studies used standard economic methodology, Stern's approach gives much greater weight to long-term ecological and economic effects. The Stern Review uses a low discount rate of 1.4 percent to balance present and future costs. Thus even though costs of aggressive action appear higher than benefits for several decades, the high potential long-term damages sway the balance in favor of aggressive action today. These are significant both for their monetary and nonmonetary impacts. In the long term, damage to the environment from global climate change will have significant negative effects on the economy, too. But the use of a standard discount rate has the effect of reducing the present value of significant long-term future damages to relative insignificance. (This is shown in Chapter 7, Table 7.2, indicating for example that at a discount rate of 5 percent the value of \$100 worth of damages 50 years in the future is evaluated in today's dollars as only \$8.71, and 100 years in the future as a mere 76 cents.)

Another difference between the two studies concerns their treatment of uncertainty. Stern's approach gives a heavier weighting to uncertain but potentially catastrophic impacts. This reflects the application of a **precautionary principle**: If a particular outcome could be catastrophic, even though it seems unlikely, strong measures should be taken to avoid it. This principle, which has become more widely used in environmental risk management, is especially important for global climate change because of the many unknown but potentially disastrous outcomes possibly associated with continued greenhouse gas accumulation (see Box 12.4). A study by Martin Weitzman argues that a serious consideration of the possibilities of catastrophic climate change can outweigh the impacts of discounting, suggesting substantial investment in reducing emissions today to avoid the possibility of future disaster—on the same principle as insuring against the uncertain possibility of a future house fire.[32]

precautionary principle the view that policies should account for uncertainty by taking steps to avoid low-probability but catastrophic events.

A third area of difference concerns the assessment of the economic costs of action to mitigate climate change. Measures taken to prevent global climate change will have economic effects on GDP, consumption, and employment, which explains the reluctance of governments to take drastic measures to reduce significantly emissions of CO_2. But these effects will not all be negative.

The Stern Review conducted a comprehensive review of economic models of the costs of carbon reduction. These cost estimates depend on the modeling assumptions that are used. As noted above, the predicted costs of stabilizing atmospheric accumulations of CO_2 at 450 ppm could range from a 3.4 percent decrease to a 3.9 percent *increase* in global GDP. The outcomes depend on a range of assumptions including:

- The efficiency or inefficiency of economic responses to energy price signals
- The availability of noncarbon **"backstop" energy technologies**
- Whether countries can trade **least-cost options** for carbon reduction using a tradable permits scheme (the economics of tradable permits were presented in Chapter 8)
- Whether revenues from taxes on carbon-based fuels are used to lower other taxes
- Whether external benefits of carbon reduction, including reduction in ground-level air pollution, are taken into account[33]

"backstop" energy technologies technologies such as solar and wind that can replace current energy sources, especially fossil fuels.

least-cost options actions that can be taken for the lowest overall cost.

Depending on which assumptions are made, policies for emissions reduction could range from a minimalist approach of slightly reducing emissions to drastic CO_2 emissions reduction of 80 percent or more. In recent years, however, the positions of Nordhaus and Stern have converged. Nordhaus, in his latest publications, uses an updated version of his model (DICE-2013) projecting a temperature increase of 3°C or more by 2100. He advocates a carbon tax of \$21 per ton of CO_2 emitted, rising rapidly over time (the economics of carbon taxes are discussed in detail in Chapter 13).[34] A modification of his model by Simon Dietz and Nicholas Stern, taking into account increased damages and the possibility of climate "tipping points" (see Box 12.4), suggests that carbon taxes should be two to seven times higher, to limit atmospheric CO_2 accumulations to 425–500 ppm and global temperature change to 1.5 to 2.0°C.[35] Thus while differences remain, the trend is generally toward recommendations for more drastic policy measures:

> While Nordhaus and Stern may differ on whether a carbon tax should be imposed either as a ramp or a steep hill, and on the appropriate discount rate for converting anticipated future damages to present terms, this debate is progressively less relevant as they both agree that the steepness of this ramp would increase, with model sophistication and with the further delay of a carbon tax.[36]

Box 12.4
CLIMATE TIPPING POINTS AND SURPRISES

Much of the uncertainty in projections of climate change relates to the issue of feedback loops. A feedback loop occurs when an initial change, such as warmer temperatures, produces changes in physical processes, which then amplify or lessen the initial effect (a response that increases the original effect is called a positive feedback loop; a response that reduces it is a negative feedback loop). An example of a positive feedback loop is when warming leads to increased melting of arctic tundra, releasing carbon dioxide and methane, which add to atmospheric greenhouse gas accumulations and speed up the warming process.

As a result of various feedback loops associated with climate change, recent evidence suggests that warming is occurring faster than most scientists predicted just five or ten years ago. This is leading to increasing concern over the potential for "runaway" feedback loops, which could result in dramatic changes in a short period. Some scientists suggest that we may be near certain climate tipping points, which, once exceeded, have the potential for catastrophic effects.

Perhaps the most disturbing possibility is the rapid collapse of the Greenland and West Antarctic Ice Sheets. A 2016 study argued that large chunks of the polar ice could melt over the next 50 years, causing a sea rise of 20 to 30 feet. The paper suggests that fresh water pouring into the oceans from melting land ice will set off a feedback loop that will cause rapid disintegration of ice sheets in Greenland and Antarctica. "That would mean loss of all coastal cities, most of the world's large cities and all their history," according to lead author Dr. James Hansen.

While rapid melting scenarios remain controversial, other dangerous feedback loops have been identified. In recent studies, scientists found that methane emissions from the Arctic have risen by almost one-third in just five years. The discovery follows a string of reports from the region in recent years that previously frozen boggy soils are melting and releasing methane in greater quantities. Such arctic soils currently lock away billions of tons of methane, a far more potent greenhouse gas than carbon dioxide, leading some scientists to describe melting permafrost as a ticking time bomb that could overwhelm efforts to tackle climate change. They fear the warming caused by increased methane emissions will itself release yet more methane and lock the world into a destructive cycle that forces temperatures to rise more rapidly than predicted.

Sources: David Adam, "Arctic Permafrost Leaking Methane at Record Levels, Figures Show," *The Guardian*, January 14, 2010, www.guardian.co.uk/environment/2010/jan/14/arctic-permafrost-methane/; Justin Gillis, "Scientists Warn of Perilous Climate Shift Within Decades, Not Centuries," *New York Times*, March 22, 2016; DeConto and Pollard, 2016.

Climate Change and Inequality

The effects of climate change will fall most heavily upon the poor of the world. Regions such as Africa could face severely compromised food production and water shortages, while coastal areas in South, East, and Southeast Asia will be at great risk of flooding. Tropical Latin America will see damage to forests and agricultural areas due to drier climate, while in South America changes in precipitation patterns and the disappearance of glaciers will significantly affect water availability.[37] While the richer countries may have the economic resources to adapt to many of the effects of climate change, without significant aid poorer countries will be unable to implement preventive measures, especially those that rely on the newest technologies. This raises fundamental issues of **environmental justice** (discussed in Chapter 3, Box 3.4) in relation to the impact of economic and political power on environmental policy on a global scale. The concept of **climate justice** is a term used for framing global warming as an ethical and political issue, rather than one that is purely environmental or physical in nature. The principles of climate justice imply an equitable sharing both of the burdens of climate change and the costs of developing policy responses (discussed further in Chapter 13).[38]

environmental justice the fair treatment of people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies.

climate justice equitable sharing both of the burdens of climate change and the costs of policy responses.

Recent studies have used geographically distributed impacts models to estimate the impacts of climate change across the global domain. As Table 12.2 indicates, the number of coastal flood victims and population at risk of hunger by 2080 will be relatively larger in Africa, South America, and Asia, where most developing countries are located.

A study published in Nature predicted that:

> If societies continue to function as they have in the recent past, climate change is expected to reshape the global economy by substantially reducing global economic output and possibly amplifying existing global economic inequalities, relative to a world without climate change. Adaptations such as unprecedented innovation or defensive investments might reduce these effects, but social conflict or disrupted trade could exacerbate them.[39]

Overall, the study projects that "the likelihood of large global losses is substantial" with the heaviest proportional losses being borne by the poorest countries.

Table 12.2 **Regional-Scale Impacts of Climate Change by 2080** (Millions of People)

Region	Population living in watersheds with an increase in water-resources stress	Increase in average annual number of coastal flood victims	Additional population at risk of hunger (figures in parentheses assume maximum CO_2 enrichment effect)
Europe	382–493	0.3	0
Asia	892–1197	14.7	266 (–21)
North America	110–145	0.1	0
South America	430–469	0.4	85 (–4)
Africa	691–909	12.8	200 (–2)

Source: Adapted from IPCC, 2007b.

Note: These estimates are based on a business-as-usual scenario (IPCC A2 scenario). The CO_2 enrichment effect is increased plant productivity, which at maximum estimates could actually decrease the number at risk of hunger.

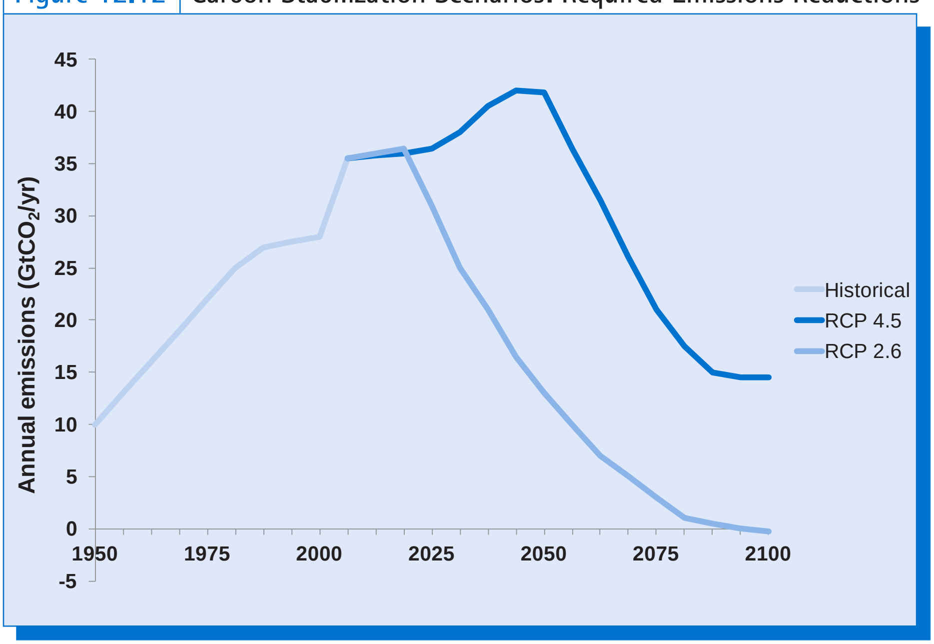
The way in which economists incorporate inequality into their analyses can have a significant impact on their policy recommendations. If all costs are evaluated in money terms, a loss of, for example, 10 percent of GDP in a poor country is likely to be much less, measured in dollars, than a loss of 3 percent of GDP in a rich country. Thus the damages from climate change in poor countries, which may be large as a percentage of GDP, would receive relatively little weight because the losses are relatively small in dollar terms. The Stern Review asserts that the disproportionate effects of climate change on the world's poorest people should increase the estimated costs of climate change. Stern estimates that, without the effects of inequity, the costs of a business-as-usual scenario could be as much as 11–14 percent of global GDP annually. Weighing the impacts on the world's poor more heavily gives a cost estimate of 20 percent of global GDP.[40]

Climate Stabilization

Assumptions about the proper way to evaluate social and environmental costs and benefits can make a big difference to policy recommendations. As we have seen, cost-benefit analyses mostly recommend action to mitigate climate change, but differ in the strength of their recommendations based on assumptions about risk and discounting. An ecologically oriented economist would argue that the fundamental issue is the stability of the physical and ecological systems that serve as a planetary climate-control mechanism. This means that **climate stabilization**, rather than economic optimization of costs and benefits, should

> **climate stabilization** the policy of reducing fossil-fuel use to a level that would not increase the potential for global climate change.

Figure 12.12 Carbon Stabilization Scenarios: Required Emissions Reductions



Source: IPCC, 2014d, *Summary for Policymakers*, p. 11.

Note: Upper line represents IPCC RCP 4.5 scenario (moderate stabilization in the range of 530–580 ppm CO_2 accumulation) and lower line represents IPCC RCP 2.6 scenario (stronger stabilization at 430–480 ppm CO_2 accumulation).

be the goal. Stabilizing greenhouse gas *emissions* is insufficient; at the current rate of emissions carbon dioxide and other greenhouse gases will continue to accumulate in the atmosphere.

Stabilizing *accumulations* of greenhouse gases will require a significant cut below present emission levels. Figure 12.12 shows the IPCC estimates of required reductions in CO_2 emissions to achieve stabilization at levels of 430–480 ppm and 530–580 ppm of CO_2 in the atmosphere. Note that for the lower stabilization level, total emissions need to fall essentially to zero in the second part of the twenty-first century. This could likely only be achieved with substantially increased global absorption of CO_2, possibly through expanding forests and modifying agricultural techniques in addition to drastic emissions reductions.

Clearly, reductions of this magnitude would imply major changes in the way that the global economy uses energy. As we saw in Chapter 11, energy efficiency and the use of renewable energy could have a significant effect in reducing emissions. Other policies could reduce emissions of other greenhouse gases and promote CO_2 absorption in forests and soils. What combination of policies can provide a sufficient response, and how have the countries of the world reacted to the issue thus far? Chapter 13 addresses these issues in detail.

Summary

Climate change, arising from the greenhouse effect of heat-trapping gases, is a global problem. All countries are involved in both its causes and consequences. Currently, greenhouse gas emissions are approximately equally divided between developed and developing countries, but emissions by developing countries will grow considerably in the coming decades.

The most recent scientific evidence indicates that effects during the twenty-first century may range from a global temperature increase of 1.5°C (2.7°F) to 4.8°C (8.6°F). In addition to simply warming the planet, other predicted effects include disruption of weather patterns and possible sudden major climate shifts.

Economic analysis of climate change involves estimating costs and benefits. The benefits in this case are the damages potentially averted through action to prevent climate change; the costs are the economic costs of shifting away from fossil-fuel dependence, as well as other economic implications of greenhouse gas reduction.

Cost-benefit studies have estimated both costs and benefits in the range of several percent of GDP. However, relative evaluation of costs and benefits depends heavily on the discount rate selected. Because damage tends to worsen over time, the use of a high discount rate leads to a lower evaluation of the benefits of avoiding climate change. In addition, effects such as species loss and effects on life and health are difficult to measure in monetary terms, as are the possibilities of uncertain but potentially catastrophic "runaway" effects. Also, depending on the assumptions used in economic models, the costs of policies to avoid climate change could range from a 4 percent decrease to a 4 percent increase in GDP.

Impacts of global climate change will fall most heavily on developing countries. Most economic analyses recommend some form of action to mitigate climate change, but vary widely in terms of the urgency and the extent of proposed remedies. Stabilizing carbon dioxide accumulations in the atmosphere at levels below 550 ppm will require drastic action to reduce emissions, implying major changes in global patterns of energy use and other policies to promote carbon reduction.

Key Terms and Concepts

adaptive strategies
avoided costs
"backstop" energy technologies
business as usual
climate stabilization
CO_2 equivalent (CO_2e)
common property resources
cost-benefit analysis
discount rate
feedback effect
future costs and benefits
global climate change
global commons
global warming
greenhouse effect
greenhouse gases
least-cost options
ocean acidification
precautionary principle
preventive strategies
public good
stock pollutant

Discussion Questions

1. What is the main evidence of global climate change? How serious is the problem, and what are its primary causes? What issues does it raise concerning global equity and responsibility for dealing with the problem?
2. Do you think that the use of cost-benefit analysis to address the problem of climate change is useful? How can we adequately value things like the melting of Arctic ice caps and inundation of island nations? What is the appropriate role of economic analysis in dealing with questions that affect global ecosystems and future generations?
3. What goals would be appropriate in responding to climate change? Since it is impossible to stop climate change entirely, how should we balance our efforts between adaptation and prevention/mitigation?

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Web Sites

1. **http://www.epa.gov/climatechange.** The global warming web site of the U.S. Environmental Protection Agency. The site provides links to information on the causes, impact, and trends related to global climate change.
2. **www.ipcc.ch/.** The web site for the Intergovernmental Panel on Climate Change, a UN-sponsored agency "to assess the scientific, technical, and socioeconomic information relevant for the understanding of the risk of human-induced climate change." Its web site provides comprehensive assessment reports on climate change including the scientific basis, impacts, adaptation, and mitigation.
3. **www.hm-treasury.gov.uk/sternreview_index.htm.** Web site for the Stern Review, providing an extensive analysis of the economics of climate change including impacts, stabilization, mitigation, and adaptation.

CHAPTER 13

Global Climate Change: Policy Responses

Contributing author Anne-Marie Codur

Chapter 13 Focus Questions

- What are the possible policy responses to global climate change?
- What does economic theory suggest about appropriate policy response?
- What climate policies have been proposed and implemented at local, national, and global levels?

13.1 ADAPTATION AND MITIGATION

As discussed in Chapter 12, the scientific evidence regarding the seriousness of global climate change supports policy action. Economic analyses of climate change have generally recommended policy changes, although with considerable variability. The Stern Review on the Economics of Climate Change, in particular, calls for "an urgent global response."[1] Recent economic analyses of climate change have placed greater emphasis on insurance against catastrophic risks and the need to adapt to inevitable climate change impacts.[2]

Policy responses to climate change can be broadly classified into two categories: **adaptive measures** to deal with the consequences of climate change and mitigation, or **preventive measures** intended to lower the magnitude or timing of climate change. Adaptive measures include:

- Construction of dikes and seawalls to protect against rising seas and extreme weather events such as floods and hurricanes.
- Shifting cultivation patterns in agriculture to adapt to changing weather conditions.
- Creating institutions that can mobilize the needed human, material, and financial resources to respond to climate-related disasters.

adaptive measures/adaptive strategies actions designed to reduce the magnitude or risk of damages from global climate change.

preventive measures/preventive strategies actions designed to reduce the extent of climate change by reducing projected emissions of greenhouse gases.

Mitigation measures include:

- Reducing emissions of greenhouse gases by meeting energy demands from sources with lower greenhouse gas emissions (e.g., switching from coal to wind energy for electricity).
- Reducing greenhouse gas emissions by increasing energy efficiency (e.g., demand-side management, as discussed in Chapter 11).
- Enhancing natural **carbon sinks**. Carbon sinks are areas where carbon may be stored; natural sinks include soils and forests. Human intervention can either reduce or expand these sinks through forest management and agricultural practices. Forests recycle carbon dioxide (CO_2) into oxygen; preserving forested areas and expanding reforestation can have a significant effect on net CO_2 emissions. Soils are also vast carbon repositories, with three times more carbon stored in soils than in the atmosphere. Restoring degraded soils could capture large quantities of CO_2.

carbon sinks portions of the ecosystem with the ability to absorb certain quantities of carbon dioxide, including forests and oceans.

cost-benefit analysis (CBA) a tool for policy analysis that attempts to monetize all the costs and benefits of a proposed action to determine the net benefit.

cost-effectiveness analysis a policy tool that determines the least-cost approach for achieving a given goal.

Economic analysis can provide policy guidance for nearly any particular preventive or adaptive measure. **Cost-benefit analysis**, discussed in Chapters 7 and 12, can present a basis for evaluating whether a policy should be implemented. However, as discussed in Chapter 12, economists disagree about the appropriate assumptions and methodologies for cost-benefit analyses of climate change. A less controversial conclusion from economic theory is that we should apply **cost-effectiveness analysis** in considering which policies to adopt. The use of cost-effectiveness analysis avoids many of the complications associated with cost-benefit analysis. While cost-benefit analysis attempts to offer a basis for deciding upon policy goals, cost-effectiveness analysis accepts a goal as given by society and uses economic techniques to determine the most efficient way to reach that goal.

In general, economists usually favor approaches that work through market mechanisms to achieve their goals. Early in the climate change debate, in 1997, a statement by leading economists endorsed market-based policies to slow climate change (see Box 13.1). Market-oriented approaches are considered cost effective; rather than attempting to control market actors directly, they shift incentives so that individuals and firms will change their behavior to take external costs and benefits into account. Examples of market-based policy tools include **pollution taxes** and **transferable, or tradable, permits**. Both of these are potentially useful tools for greenhouse gas reduction. Other relevant economic policies include measures to create incentives for the adoption of renewable energy sources and energy-efficient technology.

pollution tax(es) a per-unit tax based on the level of pollution.

transferable (tradable) permits tradable permits that allow a firm to emit a certain quantity of a pollutant.

Most of this chapter focuses on mitigation policies, but it is becoming increasingly evident that mitigation policies need to be supplemented with adaptation policies. Climate change is already occurring, and even if significant mitigation policies are implemented in the immediate future, warming and sea-level rise will continue well into the future, even for centuries.[3] The urgency and ability to institute adaptive measures varies across the world. It is the world's poor who face the greatest need to adapt but also most lack the necessary resources.

Box 13.1 ECONOMISTS' STATEMENT ON CLIMATE CHANGE

In 1997, more than 2,500 economists, including eight Nobel laureates, signed the following public statement calling for serious steps to deal with the risks of global climate change:

I. The review conducted by a distinguished international panel of scientists under the auspices of the Intergovernmental Panel on Climate Change has determined that "the balance of evidence suggests a discernible human influence on global climate." As economists, we believe that global climate change carries with it significant environmental, economic, social, and geopolitical risks, and that preventive steps are justified.

II. Economic studies have found that there are many potential policies to reduce greenhouse-gas emissions for which the total benefits outweigh the total costs. For the United States in particular, sound economic analysis shows that there are policy options that would slow climate change without harming American living standards, and these measures may in fact improve U.S. productivity in the longer run.

III. The most efficient approach to slowing climate change is through market-based policies. In order for the world to achieve its climatic objectives at minimum cost, a cooperative approach among nations is required—such as an international emissions trading agreement. The United States and other nations can most efficiently implement their climate policies through market mechanisms, such as carbon taxes or the auction of emissions permits. The revenues generated from such policies can effectively be used to reduce the deficit or to lower existing taxes.

Source: http//rprogress.org/publications/1997/econstatement.htm.

> [Climate change's] adverse impacts will be most striking in the developing nations because of their geographical and climatic conditions, their high dependence on natural resources, and their limited capacity to adapt to a changing climate. Within these countries, the poorest, who have the least resources and the least capacity to adapt, are the most vulnerable. Projected changes in the incidence, frequency, intensity, and duration of climate extremes (for example, heat waves, heavy precipitation, and drought), as well as more gradual changes in the average climate, will notably threaten their livelihoods—further increasing inequities between the developing and developed worlds.[4]

The Intergovernmental Panel on Climate Change (IPCC) has identified adaptation needs by major sectors, as shown in Table 13.1. Some of the most critical areas for adaptation include water, agriculture, and human health. Climate change is expected to increase precipitation in some areas, mainly the higher latitudes, including Alaska, Canada, and Russia, but decrease it in other areas, including Central America, North Africa, and southern Europe. A reduction in water runoff from snowmelt and glaciers could threaten the water supplies of more than a billion people in areas such as India and parts of South America. Providing safe drinking water in these regions may require building new dams for water storage, increasing the efficiency of water use, and other adaptation strategies.

Table 13.1 Climate Change Adaptation Needs, by Sector

Sector	Adaptation Strategies
Water	Expand water storage and desalination Improve watershed and reservoir management Increase water-use and irrigation efficiency and water re-useUrban and rural flood management
Agriculture	Adjust planting dates and crop locations Develop crop varieties adapted to drought, higher temperatures Improve land management to deal with floods/droughts Strengthen indigenous/traditional knowledge and practice
Infrastructure	Relocate vulnerable communities Build and strengthen seawalls and other barriers Create and restore wetlands for flood control Dune reinforcement
Human health	Health plans for extreme heat Increase tracking, early-warning systems for heat-related diseases Address threats to safe drinking water supplies Extend basic public health services
Transport	Relocation or adapt transport infrastructure New design standards to cope with climate change
Energy	Strengthen distribution infrastructure Address increased demand for cooling Increase efficiency, increase use of renewables
Ecosystems	Reduce other ecosystem stresses and human use pressures Improve scientific understanding, enhanced monitoring Reduce deforestation, increase reforestation Increase mangrove, coral reef, and seagrass protection

Source: IPCC, 2007; IPCC, 2014b.

Changing precipitation and temperature patterns have significant implications for agriculture. With moderate warming, crop yields are expected to increase in some colder regions, including parts of North America, but overall the impacts on agriculture are expected to be negative, and increasingly so with greater warming. In the U.S., climate change has worsened and lengthened the episodes of droughts in the Western States, notably California, which, as a result, has already forced farmers to adapt to less water-intensive crops, replacing orange groves and avocado trees with other tree crops, such as pomegranates or cactus-like dragonfruit.[5] Agricultural impacts are expected to be the most severe in Africa and Asia. More research is necessary to develop crops that can grow under anticipated drier weather conditions. Agriculture may need to be abandoned in some areas but expanded in others.[6]

The impacts of climate change on human health are already occurring. The World Health Organization (WHO) has estimated that more than 140,000 people per year are already dying as a direct result of climate change, primarily in Africa and Southeast Asia. The WHO estimates that after 2030, climate change will result in 250,000 additional deaths per years, caused by malnutrition, malaria, diarrhea, and heat stress. The WHO estimates direct damage costs to health at between $2–4 billion per year by 2030. WHO policy recommendations include strengthening public health systems, including increased education, disease surveillance, vaccination, and preparedness.[7]

Various estimates exist for the cost of appropriate adaptation measures. The United Nations Environment Program (UNEP) estimates that the cost of adaptation for developing nations could rise to between $140 and $300 billion per year by 2030, and between $280 and $500 billion per year by 2050. These sums significantly exceed the $100 billion per year pledged by developed nations in the 2015 Paris Agreement. UNEP warns that there will be a significant finance gap, "likely to grow substantially over the coming decades, unless significant progress is made to secure new, additional and innovative financing for adaptation." Adaptation costs are already two to three times higher than current international public funding for adaptation.[8]

13.2 CLIMATE CHANGE MITIGATION: ECONOMIC POLICY OPTIONS

The release of greenhouse gases in the atmosphere is a clear example of a negative externality that imposes significant costs on a global scale. In the language of economic theory, the current market for carbon-based fuels such as coal, oil, and natural gas takes into account only private costs and benefits, which leads to a market equilibrium that does not correspond to the social optimum. From a social perspective, the market price for fossil fuels is too low and the quantity consumed too high, as discussed in Chapter 11.

Carbon Taxes

A standard economic remedy for internalizing external costs is a per-unit tax on the pollutant. In this case, what is called for is a **carbon tax**, levied on carbon-based fossil fuels in proportion to the amount of carbon associated with their production and use. Such a tax will raise the price of carbon-based energy sources and so give consumers incentives to conserve energy overall (which would reduce their tax burden), as well as shifting their demand to alternative sources of energy that produce lower carbon emissions (and are thus taxed at lower rates). In economic terms, the level of such a tax should be based on the **social cost of carbon**—an estimate of the

carbon tax a per-unit tax on goods and services based on the quantity of carbon dioxide emitted during the production or consumption process.

social cost of carbon an estimate of the financial cost of carbon emissions per unit, including both present and future costs.

financial impact on society of carbon emissions. The U.S. Environmental Protection Agency estimated the social cost of carbon in 2016, based on varying assumptions, as being between \$11 and \$212, with a median range around \$50.[9] (As noted in Chapter 12, a major reason for differing estimates is assumptions regarding discount rates and risk/uncertainty).

Table 13.2 shows the impact that different levels of a carbon tax would have on the prices of coal, oil, and natural gas. The tax here is given in dollars per ton of CO_2 (see Box 13.2 for a discussion of the difference between a tax on carbon and a tax on CO_2). Based on energy content, measured in British Thermal Units (Btus), coal is the most carbon-intensive fossil fuel, while natural gas produces the lowest carbon emissions per Btu (Figure 13.1). Calculating the impact of a carbon tax relative to the standard commercial units for each fuel source, we see that a carbon tax of \$50 per ton of CO_2, for example, raises the price of a gallon of gasoline by about 44 cents, or 20 percent, based on 2016 prices (Figure 13.2). A tax of \$100 per ton of CO_2 equates to an increase in gasoline prices of about 88 cents per gallon. The impact of a carbon tax would be even greater for coal prices—a tax of \$50 per ton of CO_2 would increase coal prices by 262 percent. And a \$100 per ton tax would raise coal prices by a factor of five. For natural gas, although its carbon content is lower than that of gasoline, its low price (as of 2016) means that the percentage impact on price is about the same as for gasoline.

Table 13.2 Alternative Carbon Taxes on Fossil Fuels

Impact of Carbon Tax on Retail Price of Gasoline	
kg CO_2 per gallon	8.89
tonnes CO_2 per gallon	0.00889
\$/gal., \$50/tonne tax	\$0.45
\$/gal., \$100/tonne tax	\$0.89
Retail price (2016) per gallon	\$2.20
% increase, \$50/tonne tax	20.5%
% increase, \$100/tonne tax	41%
Impact of Carbon Tax on Retail Price of Coal	
kg CO_2 per short ton	2100
tonnes CO_2 per short ton	2.1
\$/short ton, \$50/tonne tax	\$105
\$/short ton, \$100/tonne tax	\$210
Retail price (2016) per short ton	\$40
% increase, \$50/tonne tax	262.5%
% increase, \$100/tonne tax	525.0%
Impact of Carbon Tax on Retail Price of Natural Gas	
kg CO_2 per 1000 cu. ft.	53.12
tonnes CO_2 per 1000 cu. ft.	0.05312
\$/1000 cu. ft., \$50/tonne tax	\$2.66
\$/1000 cu. ft., \$100/tonne tax	\$5.31
Retail price (2016)	\$12
% increase from \$50/tonne tax	22.2%
% increase from \$100/tonne tax	44.4%

Source: Carbon emissions calculated from carbon coefficients and thermal conversion factors available from the U.S. Department of Energy. All price data from the U.S. Energy Information Administration.

Box 13.2
CARBON TAX CONVERSIONS

A common point of confusion is that a carbon tax can be expressed as either a tax per unit of carbon or per unit of carbon dioxide. When comparing different carbon tax proposals, we need to be careful that we are expressing each tax in the same units. Say, for example, that an economist proposes a tax of $100 per ton of carbon, while another economist proposes a tax of $35 per ton of carbon dioxide. Which one is proposing the larger tax?

To convert between the two units, we first note the relative molecular weights of carbon and carbon dioxide (CO_2). Carbon has a molecular weight of 12, while CO_2 has a molecular weight of 44. So if we want to convert a tax of $100 per ton of carbon into a tax per ton of CO_2, we would multiply the tax by 12/44, or 0.2727:

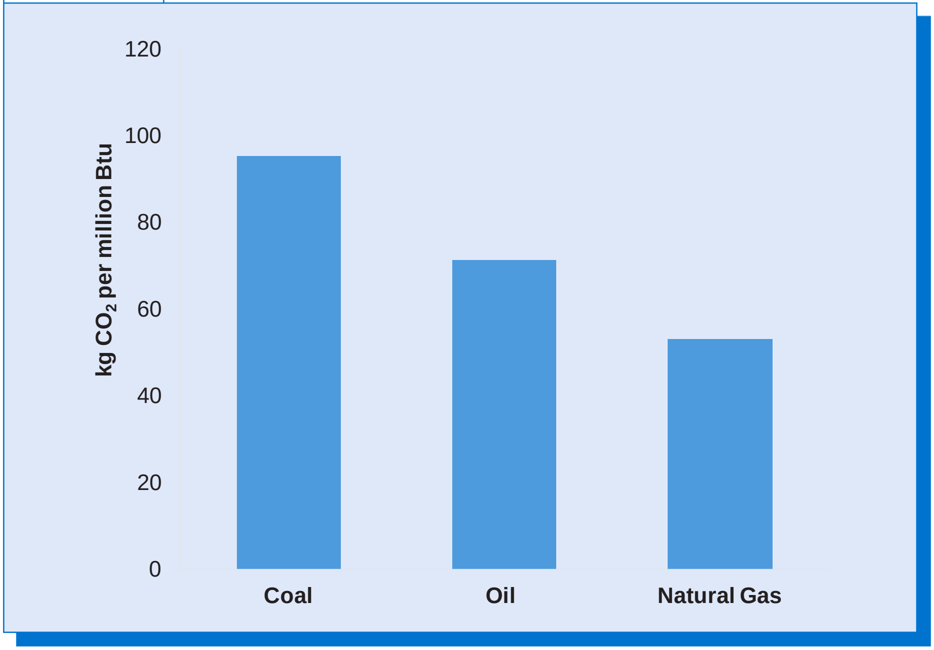
$$\$100 * 0.2727 = \$27.27.$$

So, a tax of $100 per ton of carbon is equivalent to a tax of about $27 per ton of CO_2. If we wanted instead to convert the tax of $35 per ton of CO_2, we would multiply by the inverse ratio of 44/12, or 3.6667:

$$\$35 * 3.6667 = \$128.33.$$

So, a tax of $35 per ton of CO_2 is equivalent to a tax of about $128 per ton of carbon. Using either comparison, we can conclude that a tax of $35 per ton of CO_2 is larger than a tax of $100 per ton of carbon.

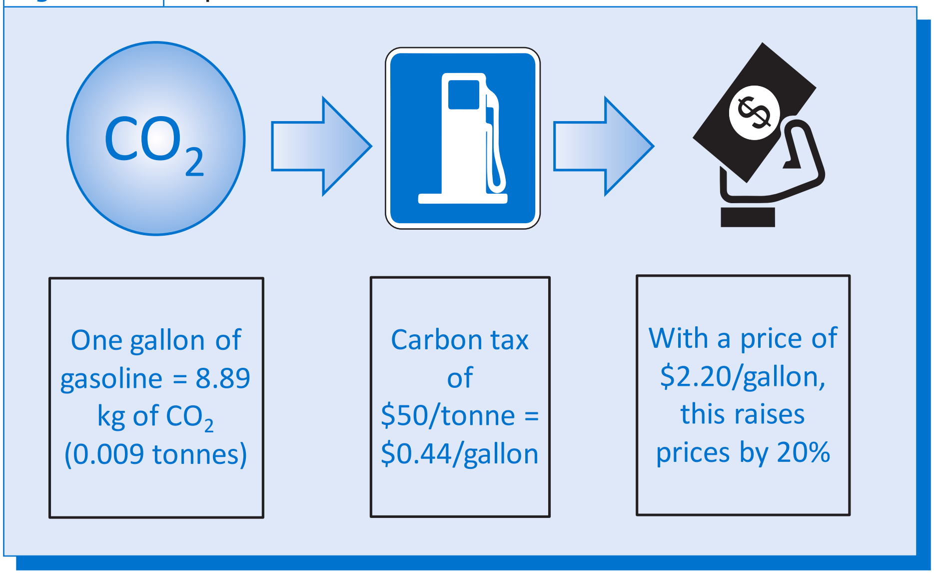
Figure 13.1 Carbon Content of Fuels



Source: Calculated from U.S. Department of Energy data.

Will these tax amounts affect people's driving or home heating habits very much, or impact industry's use of fuels? This depends on the **elasticity of demand** for these fuels. As noted earlier (see Chapter 3 Appendix), elasticity of demand is defined as:

Figure 13.2 Impact of a Carbon Tax on Gasoline Price



Source: Calculated from U.S. Department of Energy data.

$$\textit{Elasticity of demand} = \frac{\textit{Percent change in quantity demanded}}{\textit{percent change in price}}$$

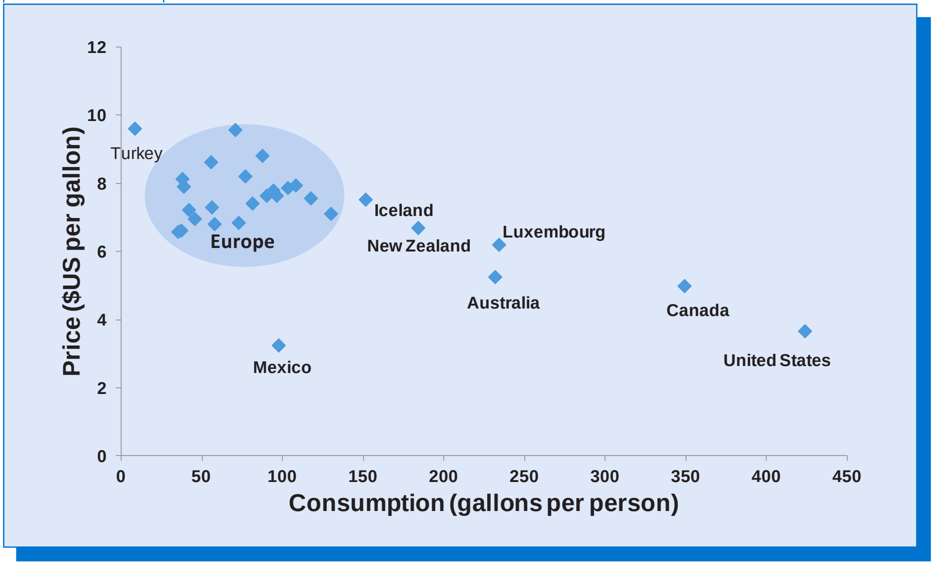
Economists have measured the elasticity of demand for different fossil fuels, particularly gasoline. (Elasticity of demand is generally negative, since a positive percent change in price causes a negative percent change in quantity demanded.) Studies indicate that in the short term (about one year or less) elasticity estimates ranged from −0.03 to −0.25. This means that a 10 percent increase in the price of gasoline would be expected to decrease gasoline demand in the short term by about −0.3 to −2.5 percent.[10]

In the long term (about five years or so) people are more responsive to gasoline price increases, as they have time to purchase different vehicles and adjust their driving habits. The average long-term elasticity of demand for motor fuels, based on 51 estimates, is −0.64.[11] According to Table 13.2, a tax of \$50 per ton of CO_2 would increase the price of gasoline by about 20 percent, adding 44 cents per gallon to the price of gasoline based on 2016 prices. A long-term elasticity of –0.64 suggests that after people have time to fully adjust to this price change, the demand for gasoline should decline by about 13 percent.

Figure 13.3 shows a cross-country relationship between gasoline prices and per capita consumption. (Since the cost of producing a gallon of gasoline varies little across countries, variations in the price of a gallon in different countries is almost solely a function of differences in taxes.) Note that this relationship is similar to that of a demand curve: higher prices are associated with lower consumption, and lower prices with higher consumption.

The relationship shown here, however, is not exactly the same as a demand curve; since we are looking at data from different countries, the assumption of "other things equal," which is needed to construct a demand curve, does not hold. Differences in demand may, for example, be in part a function of differences in income levels rather than prices. Also, people in the United States may drive more partly because travel distances (especially in the

Figure 13.3 Gasoline Price versus Consumption in Industrial Countries, 2012



Sources: U.S. Energy Information Administration database, *International Energy Statistics*; *GIZ*, International Fuel Prices 2012/2013; World Bank, *World Development Indicators* (Population).

Note: Shaded area represents price/consumption range typical of West European countries.

western United States) are greater than in many European countries, and public transportation options fewer. But there does seem to be a clear price/consumption relationship. The data shown here suggest that it would take a fairly big price hike—in the range of $0.50–$1.00 per gallon or more—to affect fuel use substantially.

Would a large gasoline tax increase, or a broad-based carbon tax, ever be politically feasible? Especially in the United States, high taxes on gasoline and other fuels would face much opposition. As Figure 13.3 shows, the United States has by far the highest gasoline consumption per person and the lowest prices outside the Middle East. But let us note two things about the proposal for substantial carbon taxes:

- First, revenue recycling could redirect the revenue from carbon and other environmental taxes to lower other taxes. Much of the political opposition to high energy taxes comes from the perception that they would be an *extra* tax—on top of the income, property, and social security taxes that people already pay. If a carbon tax were matched, for example, with a substantial cut in income or social security taxes, it might be more politically acceptable.
- The idea of increasing taxes on economic "bads," such as pollution, while reducing taxes on things we want to encourage, such as labor and capital investment, is fully consistent with principles of economic efficiency. Rather than a net tax increase, this would be **revenue-neutral tax shift**—the total amount that citizens pay to the government in taxes is essentially unchanged. Some of the tax revenues could also be used to provide relief for low-income people to offset the burden of higher energy costs.

revenue-neutral tax shift policies that are designed to balance tax increases on certain products or activities with a reduction in other taxes, such as a reduction in income taxes that offsets a carbon-based tax.

- Second, if such a revenue-neutral tax shift did take place, individuals or businesses whose operations were more energy efficient would actually save money overall. The higher cost of energy would also create a powerful incentive for energy-saving technological innovations and stimulate new markets. Economic adaptation would be easier if the higher carbon taxes (and lower income and capital taxes) were phased in over time.

Tradable Permits

cap and trade a tradable permit system for pollution emissions.

An alternative to a carbon tax is a system of tradable carbon permits, also called **cap-and-trade**. A carbon trading scheme can be implemented at the state or national level, or could include multiple countries. A national permit system could work as follows, as discussed in Chapter 8:

- Each emitting firm would be allocated a specific permissible level of carbon emissions. The total number of carbon permits issued would equal the desired national goal. For example, if carbon emissions for a particular country are currently 40 million tons and the policy goal is to reduce this by 10 percent (4 million tons), then permits would be issued to emit only 36 million tons. Over time, the goal could be increased, with the result that fewer permits would be issued in future periods.
- Permits are allocated to individual carbon-emitting sources. Including all carbon sources (e.g., all motor vehicles) in a trading scheme is generally not practical. It is most effective to implement permits as far upstream in the production process as possible to simplify the administration of the program and cover the most emissions. ("Upstream" here denotes an early stage in the production process, as discussed in Chapter 3 regarding a pollution tax.) Permits could be allocated to the largest carbon emitters, such as power companies and manufacturing plants, or even further upstream to the suppliers through which carbon fuels enter the production process—oil producers and importers, coal mines, and natural gas drillers.
- These permits could initially be allocated for free on the basis of past emissions or auctioned to the highest bidders. As discussed in Chapter 8, the effectiveness of the trading system should be the same regardless of how the permits are allocated. However, there is a significant difference in the distribution of costs and benefits: Giving permits out for free essentially amounts to a windfall gain for polluters, while auctioning permits imposes real costs upon firms and generates public revenues.
- Firms are able to trade permits freely among themselves. Firms whose emissions exceed the number of permits they hold must purchase additional permits or else face penalties. Meanwhile firms that are able to reduce their emissions below their allowance at low cost will seek to sell their permits for a profit. A permit price will be determined through market supply and demand. It may also be possible for environmental groups or other organizations to purchase permits and retire them—thus reducing overall emissions.
- In an international system, countries and firms could also receive credit for financing carbon reduction efforts in other countries. For example, a German firm could get credit for installing efficient renewable electric generating equipment in China, replacing highly polluting coal plants.

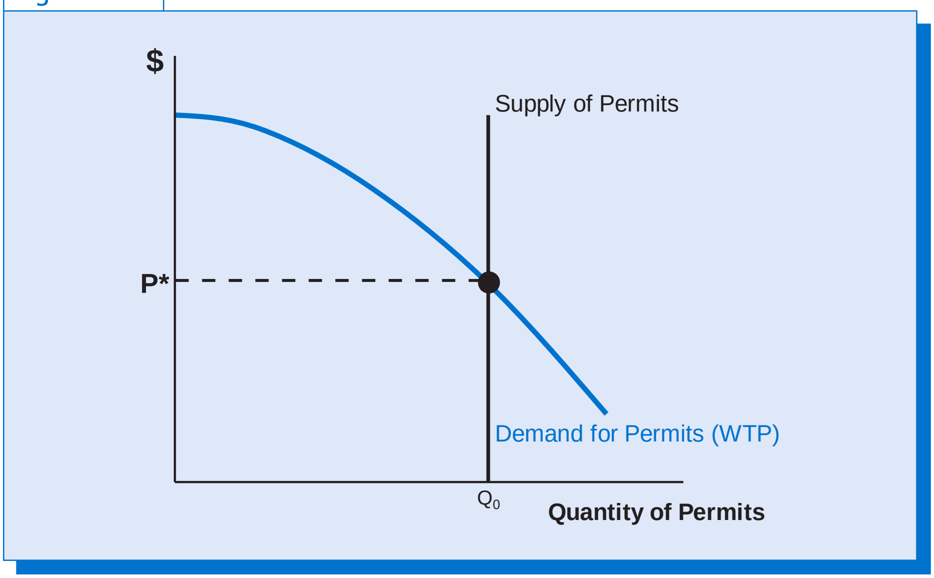
A tradable permit system encourages the least-cost carbon reduction options to be implemented, as rational firms will implement those emission-reduction actions that are cheaper than the market permit price. As discussed in Chapter 8, tradable permit systems have been successful in reducing sulfur and nitrogen oxide emissions at low cost. Depending on the allocation of permits in an international scheme, it might also mean that developing countries could transform permits into a new export commodity by choosing a non-carbon path for their energy development. They would then be able to sell permits to industrialized countries that were having trouble meeting their reduction requirements. Farmers and foresters could also get carbon credits for using methods that store carbon in soils or preserve forests.

While the government sets the number of permits available, the permit price is determined by market forces. In this case, the supply curve is fixed, or vertical, at the number of permits allocated, as shown in Figure 13.4. The supply of permits is set at Q_0. The demand curve for permits represents firms' willingness to pay for them. Their maximum willingness to pay for permits is equal to the potential profits they can earn by emitting carbon.

Assume that the permits will be auctioned off one by one to the highest bidders (a process known as a sequential auction). Figure 13.4 shows that the willingness to pay for the first permit would be quite high, as a particular firm stands to make a relatively large profit by being allowed to emit one unit of carbon. For the second permit, firms that failed to obtain the first permit would be expected to simply repeat their bids. The firm that successfully bid for the first permit could also bid for the second permit, but would be expected to bid a lower amount assuming their marginal profits are declining (i.e., their supply curve slopes upward, as is normal).

Regardless of whether the same firm wins the bid for the second permit, or a new firm, the selling price for the second permit would be lower. This process would continue, with all successive permits selling for lower prices, until the last permit is auctioned off. The selling price of this permit, represented by P^* in the graph, is the market-clearing permit price. We can also interpret P^* as the marginal benefit, or profit, associated with the right to emit the Q_0th unit of carbon.

Figure 13.4 Determination of Carbon Permit Price



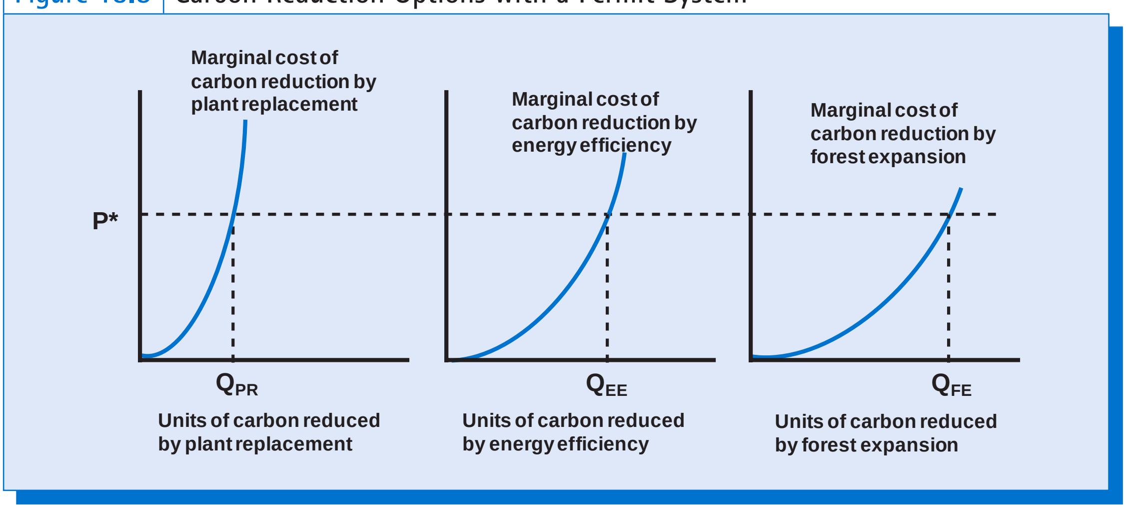
Note: WTP = willingness to pay.

While permits could theoretically sell for different prices in a sequential auction, tradable permit markets are normally set up so that all permits sell for the market-clearing price. This is the case for the acid rain program in the United States, which has operated since 1995 and is widely considered to be a successful emissions trading program, as discussed in Chapter 8, Box 8.2. In that program, all parties interested in purchasing permits make their bids, indicating how many permits they are willing to purchase at what price. Whoever bids the highest gets the number of permits that were requested. Then the second-highest bidders get the number of permits they applied for, and so on until all permits are allocated. The selling price of all permits is the winning bid for the very last permit available. This would be *P** in Figure 13.4. All bidders who bid below this price do not receive any permits.

Another important point is that each firm can choose to reduce its carbon emissions in a cost-effective manner. Firms have various options for reducing their carbon emissions. Figure 13.5 shows an example in which a firm has three carbon reduction strategies: replacing older manufacturing plants, investing in energy efficiency, and funding forest expansion to increase carbon storage in biomass. In each case, the graph shows the marginal costs of reducing carbon emissions through that strategy. These marginal costs generally rise as more units of carbon are reduced, but they may be higher and increase more rapidly for some options than others.

In this example, replacement of manufacturing plants using existing carbon-emitting technologies is possible but will tend to have high marginal costs—as shown in the first graph in Figure 13.5. Reducing emissions through greater energy efficiency has lower marginal costs, as seen in the middle graph. Finally, carbon storage through forest area expansion has the lowest marginal costs. The permit price *P** (as determined in Figure 13.4) will govern the relative levels of implementation of each of these strategies. Firms will find it profitable to reduce emissions using a particular strategy so long as the costs of that option are lower than the cost of purchasing a permit. The analysis indicates that forest expansion would be used for the largest share of the reduction (Q_{FE}), but plant replacement and energy efficiency would also contribute shares (Q_{PR} and Q_{EE}) at the market equilibrium. Firms (and countries if the program is international) that participate in such a trading scheme can thus decide for themselves how much of each control strategy to implement and will

Figure 13.5 Carbon Reduction Options with a Permit System



Note: Marginal costs shown here are hypothetical.

naturally favor the least-cost methods. This will probably involve a combination of different approaches. In an international program, suppose that one country undertakes extensive reforestation. It is then likely to have excess permits, which it can sell to a country with few low-cost reduction options. The net effect will be the worldwide implementation of the least-cost reduction techniques.

This system combines the advantages of economic efficiency with a guaranteed result: reduction in overall emissions to the desired level. The major problem, of course, is achieving agreement on the initial number of permits, and deciding whether the permits will be allocated freely or auctioned off. There may also be measurement problems and issues such as whether to count only commercial carbon emissions or to include emissions changes that result from land use changes, such as those associated with agriculture and forestry. Including agriculture and forestry has the advantage of broadening the scheme to include many more reduction strategies, possibly at significantly lower cost, but it may be more difficult to get an accurate measure of carbon storage and release from land use change.

Carbon Taxes or Cap and Trade?

There is a lively debate regarding which economic approach should be used to reduce carbon emissions. Carbon taxes and a cap-and-trade approach have important similarities but also important differences.

As discussed in Chapter 8, both pollution taxes and cap-and-trade can, in theory, achieve a given level of pollution reduction at the least overall cost. Both approaches will also result in the same level of price increases to final consumers, and both create a strong incentive for technological innovation. Both approaches can raise the same amount of government revenue, assuming all permits are auctioned off, and can be implemented upstream in production processes to cover the same proportion of total emissions.

Yet the two policies have several important differences. Some of the advantages of a carbon tax include:

- In general, a carbon tax is considered simpler to understand and more transparent than a cap-and-trade approach. Cap-and-trade systems can be complex and require new bureaucratic institutions to operate.
- As we saw in Chapter 8, with technological change that lowers the cost of carbon reduction, a carbon tax will automatically further reduce carbon emissions. In a cap-and-trade program, technological change will instead reduce the price of permits, probably resulting in some firms actually emitting more carbon.
- A carbon tax could probably be implemented more quickly. Given the need to address climate change as soon as possible, it may be inadvisable to spend years working out the details and implementation of a cap-and-trade program.
- Perhaps the most important advantage of a carbon tax is that it provides greater price predictability. If businesses and households know what future taxes will be on fossil fuels and other greenhouse gas-emitting products, they can invest accordingly. For example, whether a business invests in an energy efficient heating and cooling system depends on its expectations of future fuel prices. In a cap-and-trade system, permit prices could vary considerably, leading to **price volatility** that makes planning difficult. A carbon tax, by contrast, provides a degree of price stability, especially if carbon tax levels are published years into the future. (Carbon tax advantages summarized from www.carbontax.org/faqs/)

price volatility rapid and frequent changes in price, leading to market instability.

The advantages of a cap-and-trade system include:

- Even though a cap-and-trade system ultimately results in the same level of price increases to consumers and businesses, it avoids the negative connotations of a "tax." So a cap-and-trade system often generates less political opposition than a carbon tax.
- Some businesses favor cap-and-trade because they believe that they can successfully lobby governments for free permits, rather than having to purchase them at auction. Distributing permits for free in the early stages of a cap-and-trade program can make it more politically acceptable to businesses.
- The greatest advantage of a cap-and-trade approach is that emissions are known with certainty because the government sets the number of available permits. Since the policy goal is ultimately to reduce carbon emissions, a cap-and-trade approach does this directly while a carbon tax does it indirectly through price increases. Using a cap-and-trade approach, we can achieve a specific emissions path simply by setting the number of permits. In a carbon tax system, achieving a specific emissions target may require numerous adjustments to the tax rates, which may be politically very difficult.

The choice of instrument—carbon tax or cap-and-trade—mainly depends on whether policy makers are more concerned with price uncertainty or emissions uncertainty. (Recall the discussion on price versus quantity instruments in Chapter 8). If you take the perspective that price certainty is important because it allows for better long-term planning, then a carbon tax is preferable. If you believe that the relevant policy goal is to reduce carbon emissions by a specified amount with certainty, then a cap-and-trade approach is preferable, although it may lead to some price volatility. Another practical difference appears to be that carbon tax revenues are more often refunded to taxpayers or used in general government spending, while cap-and-trade auction revenues are more often used to support such "green" investments as renewable energy, energy efficiency, and forest conservation.[12]

Other Policy Tools: Subsidies, Standards, R&D, and Technology Transfer

Political hurdles may prevent the adoption of sweeping carbon taxes or transferable permit systems. Fortunately, a variety of other policy measures have the potential to lower carbon emissions. Even with implementation of a widespread carbon tax or cap-and-trade system, supplemental policies may still be necessary to reduce carbon emissions sufficiently to keep warming within acceptable levels. These policies are generally not considered to be sufficient by themselves, but they may be important components of a comprehensive approach. To some extent these policies are already being implemented in various countries. These policies include:

- *Shifting subsidies from carbon-based to non-carbon-based fuels*. Many countries currently provide direct or indirect subsidies to fossil fuels, as discussed in Chapter 11. The elimination of these subsidies would alter the competitive balance in favor of alternative fuel sources. If these subsidy expenditures were redirected to renewable sources, especially in the form of tax rebates for investment, it could promote a boom in investment in renewables.

- *The use of **efficiency standards** for machinery and appliances, and fuel-economy standards or requirements for low-carbon fuels.* By imposing standards that require greater energy efficiency or lower carbon use, technologies and practices can be altered in favor of a low-carbon path.
- *Research and development (R&D) expenditures promoting the commercialization of alternative technologies.* Both government R&D programs and favorable tax treatment of corporate R&D for alternative energy can speed commercialization. The existence of non-carbon "backstop" technologies significantly reduces the economic cost of measures such as carbon taxes, and if the backstop were to become fully competitive with fossil fuels, carbon taxes would be unnecessary.
- ***Technology transfer** to developing countries.* The bulk of projected growth in carbon emissions will come in the developing world. Many energy development projects are now funded by agencies such as the World Bank and regional development banks. To the extent that these funds can be directed toward non-carbon energy systems, supplemented by other funds dedicated specifically to alternative energy development, it will be economically feasible for developing countries to turn away from fossil-fuel intensive paths, achieving significant local environmental benefits at the same time.

efficiency standards regulations that mandate efficiency criteria for goods, such as fuel economy standards for automobiles.

technology transfer the process of sharing technological information or equipment, particularly among countries.

13.3 CLIMATE CHANGE: THE TECHNICAL CHALLENGE

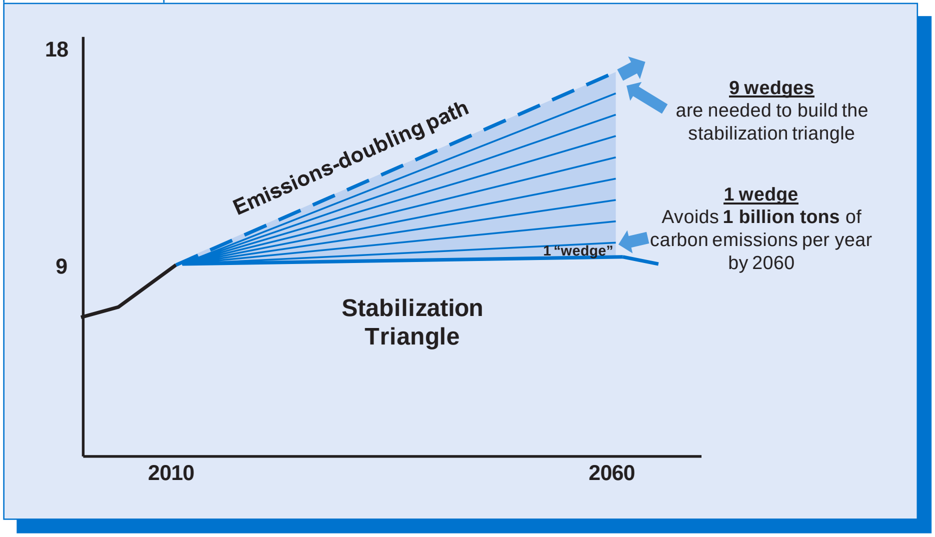
Meeting the climate change challenge requires both behavioral change and technological change. Economic policy instruments such as carbon taxes, cap-and-trade, and subsidies use incentives to motivate changes in behavior. For example, a carbon tax that raises the price of gasoline will create incentives to drive less or buy a more fuel-efficient vehicle. But we can also look at climate change from a technical perspective rather than a behavioral perspective. Economic policies can create powerful incentives for technological changes. Because of higher gas prices as a result of a carbon tax, the increased demand for high-efficiency vehicles would motivate automobile companies to direct more of their investments to hybrid and electric vehicles.

It is worthwhile to consider what needs to be done in response to climate change from a technical perspective—not just to gain a greater understanding of the issues but to also gain some insights for appropriate policies. We now summarize two well-known analyses of the technical aspects of carbon mitigation.

Climate Stabilization Wedges

Some proposals for carbon mitigation require significant technological advancement, such as the widespread use of artificial photosynthesis, carbon capture and storage, or nuclear fusion. The future cost and technical feasibility of these technologies remain uncertain. Ideally, we could reduce carbon emissions sufficiently using existing technologies or those reasonably expected to be available in the near future. One way of summarizing the potential for scaling up existing technologies is the "carbon wedge" concept proposed by physical scientists Stephen Pacala and Robert Socolow.[13]

Figure 13.6 Climate Stabilization Wedges



Sources: Pacala and Socolow, 2004; Socolow and Pacala, 2006; Socolow, 2011.

climate stabilization wedge a concept in which specific mitigation actions are presented to reduce projected global greenhouse gas emissions by one gigaton each (one gigaton reduction equals one wedge).

They present the climate challenge as shown in Figure 13.6. Under a business-as-usual (BAU) scenario, carbon emissions are expected to approximately double during the 50 years from 2010 to 2060, from about 9 billion tons of carbon per year to 18 billion tons. Pacala and Socolow identify specific policies that would each effectively reduce total emissions by 1 billion tons per year by 2060. Each of these actions produces a **climate stabilization wedge** that moves emission down from the BAU scenario. Thus if nine of these wedges were implemented, carbon emissions would remain steady over the next 50 years, even as population expands and economies grow.

The proposed policies are broadly divided into three categories: increased energy efficiency, energy supply-side shifts, and carbon storage. Possible policies include:

- Double fuel efficiency of 2 billion cars from 30 to 60 miles per gallon (mpg).
- Decrease the number of car miles traveled globally by half.
- Use best-efficiency practices in all residential and commercial buildings.
- Produce current coal-based electricity with twice today's efficiency.
- Replace 1,400 coal electricity plants with natural gas-powered facilities.
- Capture and store emissions from 800 coal electricity plants.
- Add double the current global nuclear capacity, displacing coal plants.
- Add 2 million 1-Megawatt wind turbines (about 5 times 2015 capacity).
- Add 2,000 Gigawatts of photovoltaic power (about 11 times 2015 capacity).
- Use 40,000 square kilometers of solar panels (or 4 million wind turbines) to produce hydrogen for fuel cell cars.

- Eliminate tropical deforestation.
- Adopt conservation tillage in all agricultural soils worldwide.[14]

All of these policies would need to be implemented on a global, rather than national, scale. Also, as indicated by Figure 12.11 in the previous chapter, keeping emissions constant over the next 50 years will not be sufficient to keep warming to acceptable levels. Thus more than nine "wedges" will be required to stabilize atmospheric accumulations of carbon. The wedges concept, though, does indicate significant potential from existing technologies:

> None of the options is a pipe dream or an unproven idea. Today, one can buy electricity from a wind turbine, PV array, gas turbine, or nuclear power plant. One can buy hydrogen produced with the chemistry of carbon capture, biofuel to power one's car, and hundreds of devices that improve energy efficiency. One can visit tropical forests where clear-cutting has ceased, farms practicing conservation tillage, and facilities that inject carbon into geologic reservoirs. Every one of these options is already implemented at an industrial scale and could be scaled up further over 50 years to provide at least one wedge.[15]

Significant policy changes will be needed to implement these wedges on a global scale. Most important, Pacala and Socolow note the need for carbon to be properly priced, with a suggested price of \$100–\$200 per ton of carbon (\$27–\$55 per ton of CO_2). This would equate to about 25 cents per gallon of gasoline.

They also address the path of carbon emissions for developing and developed countries. If members of the Organization for Economic Cooperation and Development (OECD) were to reduce their emissions by 60 percent over the next 50 years, emissions could theoretically grow by 60 percent in the non-OECD countries over the same time period, allowing them space for economic development while keeping total emissions stable. Yet even with this allocation, per capita emissions would still be twice as high in the OECD countries as in the developing countries. And, as noted in Chapter 12, stabilizing emissions will not be sufficient to avert the worst impacts of climate change—significant overall global reduction will be needed.

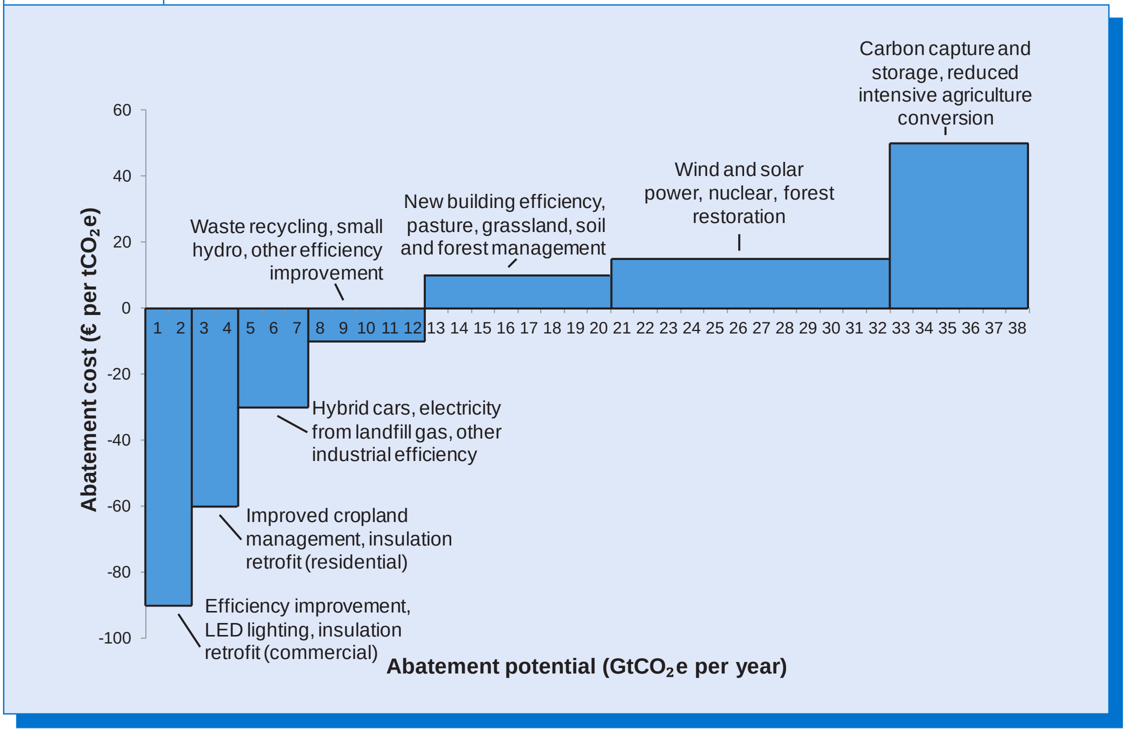
Greenhouse Gas Abatement Cost Curves

The climate stabilization wedges analysis does not address the costs of each wedge. Obviously some wedges would be cheaper than others to implement. Depending on the social cost of carbon emissions, some wedges may not provide net benefits to society. For a more complete economic analysis, we also need to consider costs.

Another well-known analysis, by McKinsey & Company, estimates both the costs and the potential carbon reduction of more than 200 greenhouse gas mitigation, or abatement, options on a global scale. The various options are arranged in order of cost, from lowest cost to highest. The economic logic is that it makes sense to implement actions that reduce carbon at the lowest per-unit costs first and then proceed to more costly actions. The results of their analysis are presented in Figure 13.7. The costs are estimated in euros, but the analysis covers worldwide reduction possibilities.[16]

This figure takes a little explanation. The *y*-axis indicates the cost range for each abatement option, measured in euros per ton of CO_2 reduction per year (or an amount equivalent to one ton of CO_2 for reductions in other gases such as methane). The thickness of the bar represents the amount of CO_2 emissions that can be avoided by each action. The cost of policies such as building insulation, increased efficiency, and waste recycling is

Figure 13.7 Global Greenhouse Gas Abatement Cost Curve for 2030



Source: Adapted from McKinsey & Company, 2009.

in the *negative* range. This means that these policies would actually save money, regardless of their effect on CO_2 emissions. So even if we did not care about climate change and the environment, it would make sense to insulate buildings, increase appliance efficiency, and recycle wastes, solely on long-term financial grounds.

The *x*-axis tells us the cumulative reduction in CO_2 equivalent emissions, relative to a BAU scenario, if we were to implement all the actions to the left. So if we were to implement all negative-cost options, including improving efficiency of air-conditioning, lighting systems, and water heating, total CO_2 equivalent reduction would be about 12 billion tons (Gt) per year, all while saving money!

Moving farther to the right, actions are identified that do entail positive costs. In other words, for all these other actions it does cost us money to reduce CO_2 emissions. Figure 13.7 shows all actions that reduce CO_2 emissions for a cost of less than €60 per ton, including expanding wind and solar energy, expanding nuclear energy, improved forest management and reforestation, and implementing carbon capture and storage (CCS). ("Low penetration" wind is defined as expanding wind energy to provide as much as 10 percent of electricity supplies, while "high penetration" expands wind energy further, at slightly higher cost.)

If all these actions were implemented, total CO_2-equivalent reduction would be 38 billion tons per year. Total global CO_2 equivalent emissions, including all greenhouse gases and emissions from land use change, are currently about 50 billion tons per year, projected to rise to about 70 Gt by 2030. Thus instead of emitting 70 Gt per year in 2030, we would be emitting only 32 Gt—a decrease of 18 Gt below current levels. Further reduction could be achieved at slightly higher cost, especially by more extensive expansion of wind and solar energy. (This analysis does not take into account likely cost reductions for renewable energy). The total cost of implementing all options in Figure 13.7, considering that some options actually save money, is estimated to be less than 1 percent of global GDP in 2030. The report notes that delaying action by just 10 years makes keeping warming under 2°C extremely difficult.

Policy recommendations to achieve the reductions represented in Figure 13.7 include:

- Establish strict technical standards for efficiency of buildings and vehicles.
- Establish stable long-term incentives for power producers and industrial companies to invest in and deploy efficient technologies.
- Provide government support for emerging efficiency and renewable energy technologies, through economic incentives and other policies.
- Ensure efficient management of forests and agriculture, particularly in developing countries.[17]

Again we see that instituting a carbon price is a part of a broader policy approach. A carbon tax or cap-and-trade program would create an incentive for the actions in Figure 13.7, but it does not guarantee that they will occur. In theory, we should already be using all the negative-cost options even in the absence of a carbon price, yet we are not. Standards and mandates can be an effective complement to a carbon price to ensure that cost-efficient actions are implemented. Potential policies could include efficiency standards for appliances, lighting, and building insulation.

How reliable is this abatement cost curve analysis? The McKinsey study has been subject to criticism both for underestimating and overestimating some costs. Also, some actions that are technically feasible, like reducing emissions from agricultural and forestry practices, may be difficult to achieve in practice due to political and institutional barriers.[18] Nonetheless, abatement costs curves such as those presented in the McKinsey study illustrate the basic principle that many low-cost or no-cost actions could be taken to reduce carbon emissions. Emissions growth is, therefore, not inevitable; substantial emissions reduction below current levels can be achieved at modest economic cost.

13.4 CLIMATE CHANGE POLICY IN PRACTICE

Climate change is an international environmental issue. In economic theory terms, as we noted in Chapter 12, climate change is a public good issue, requiring global collaboration to achieve effective results. Since the United Nations Framework Convention on Climate Change (UNFCCC) was first established in 1992, there have been extensive international discussions, known as "Conferences of the Parties" or COPs, aimed at reaching a global agreement on emissions reduction (see Table 13.3).

The first comprehensive international agreement on climate change was the Kyoto Protocol, adopted at the third COP in 1997, which has now expired. Under the Kyoto treaty, industrial countries agreed to emissions reduction targets by 2008–2012 compared to their baseline emissions, set to 1990 levels. For example, the United States agreed to a 7 percent reduction, France to an 8 percent reduction, and Japan to a 6 percent reduction. The average target was a cut of around 5 percent relative to 1990 levels. Developing countries such as China and India were not bound to emissions targets under the treaty, an omission that the United States and some other countries protested. Under President George W. Bush, the U.S. refused to ratify the Kyoto Protocol. But despite the U.S. withdrawal, the Kyoto Protocol entered into force in early 2005.

Table 13.3 Important Events in International Climate Change Negotiations

Year, Location	Outcome
1992, Rio de Janeiro	UN Framework Convention on Climate Change (UNFCCC). Countries agree to reduce emissions with "common but differentiated responsibilities."
1995, Berlin	The first annual Conference of the Parties to the framework, known as a COP. U.S. agrees to exempt developing countries from binding obligations.
1997, Kyoto	At the third Conference of the Parties (COP-3) the Kyoto Protocol is approved, mandating developed countries to cut greenhouse gas emissions relative to baseline emissions by 2008-2012 period.
2001, Bonn	COP-6 reaches agreement on terms for compliance and financing. Bush administration rejects the Kyoto Protocol; U.S. is only an observer at COP-6.
2009, Copenhagen	COP-15 fails to produce a binding post-Kyoto agreement, but declares the importance of limiting warming to under 2°C. Developed countries pledge $100 billion in climate aid to developing countries.
2011, Durban	(COP-17) Participating countries agreed to adopt a universal legal agreement on climate change as soon as possible, and no later than 2015, to take effect by 2020.
2015, Paris	(COP-21) 195 nations sign the Paris Agreement, providing for worldwide voluntary actions (known as Nationally Determined Contributions or NDCs)

The results of the Kyoto Protocol were mixed. Some nations, such as Canada and the U.S., increased rather than reduced emissions; Canada withdrew from the Protocol, and the U.S. never entered it. Some European countries met or exceeded their targets, while others fell short. Russia and most East European countries considerably exceeded their targets, not as a result of deliberate policy but rather as a byproduct of communism's economic collapse in the early 1990s. The overall Kyoto target was technically achieved, but only as a result of this significant drop in Russian and Eastern European emissions.

In addition, we need to consider the effects of trade (discussed further in Chapter 21). In the Kyoto framework, emissions released during production of goods were assigned to the country where production takes place, rather than where goods are consumed. Therefore, the "outsourcing" of carbon emissions through imports from developing countries, especially China, was not included in official accounting. Considering the full country **carbon footprint**, taking trade into account, the progress made under Kyoto was very limited, with Europe's savings reduced to just 1 percent from 1990 to 2008, and the developed world as a whole seeing its emissions rise by 7 percent in the same period (25 percent for the U.S., when trade is included). Moreover, Kyoto placed no restrictions on emissions from developing countries, meaning that overall global emissions continued to grow during the Kyoto period, as shown in Figure 12.1 in the previous chapter.[19]

carbon footprint total carbon emissions, direct and indirect, resulting from the consumption of a nation, institution, or individual.

But if the Kyoto protocol was a failure in its inability to slow down global emissions, it nevertheless provided an important first step in global climate diplomacy, and from the failures of Kyoto and its aftermath, countries learned lessons that proved useful in the later phases of those global negotiations.

The Paris Agreement of 2015

After efforts to secure a binding global agreement on emissions reductions failed at COP-15 in Copenhagen in 2009, it became increasingly obvious to negotiators that another approach would be needed in order to win broad support. The Copenhagen conference parties agreed only that the goal for future rounds of negotiations would be to keep the global temperature warming below the threshold of 2°C above pre-industrial levels. The most contentious point of disagreement was the question of whether developing countries should be bound by mandatory cuts in emissions. While some countries, particularly the United States, argued that all participants should agree to reductions, developing countries contended that mandatory cuts would limit their economic development and reinforce existing global inequities.

After the failure of Copenhagen, the idea of a binding agreement was rejected as unfeasible. In its place, negotiators came up with the idea that countries would instead propose their own voluntary goals, no matter how low or high—the hope being that countries would eventually feel "peer-pressure" to set the most ambitious possible goals within their reach. This new negotiating strategy laid the foundations for the global agreement reached at the twenty-first Conference of the Parties (COP-21) in Paris. In the months that preceded the COP-21, 186 countries submitted their NDCs—nationally determined contributions—indicating their willingness to contribute to the reduction of global CO_2 emissions.

nationally determined contribution (NDC) a voluntary planned reduction in CO_2 emissions, relative to baseline emissions, submitted by participating countries at the Paris Conference of the Parties (COP-21) in 2015.

The Paris Agreement, negotiated by 195 national delegations, formally expressed the global aim of holding temperatures to no more than 2°C above preindustrial levels, with a more ambitious target of 1.5°C. Since the current total of country pledges (NDCs) is not sufficient to secure the global goal of keeping warming under 2°C, the agreement includes five-year cycles for countries to review their goals and ratchet up their targets, in order to reach more ambitious goals. The negotiating process has been designed to put pressure on every country to comply with its own pledges and to increase them over time. A strong transparency and accountability regime is built into the agreement, based on regular inventories, regular reporting of the progress countries are making toward their targets, and regular review by expert teams. The Paris Agreement entered into force, with over 80 countries representing over 60 percent of global emissions ratifying the agreement by the end of 2016, just a year after it was negotiated, a record speed for international agreements. Despite subsequent rejection of the agreement's provisions by the United States under the Trump administration, it remains in force—though compliance with the targets is voluntary. A related binding agreement establishing specific timetables to eliminate the production of hydrofluorocarbons (HFCs), powerful greenhouse gases used in air-conditioners and refrigerators, was agreed on in October 2015.[20]

The Paris Agreement also provides for continuing financial and technical support to developing countries to help them adapt to the disruptive consequences of climate change, as well as support for a transition away from fossil fuels toward cleaner renewable energy sources. The agreement included a loss-and-damage clause recognizing the importance of addressing the adverse effects of climate change in developing countries. While the agreement does not accept liability or provide for compensation, it does offer several conditions where support may be given. Starting in 2020, industrialized nations have pledged $100 billion a year in financial and technical aid to developing countries to fight climate change.[21]

Many voices in the developing world have warned that $100 billion will fall far short of what is really needed, and that a conservative figure would be closer to $600 billion, which is about 1.5 percent of the GDP of industrialized nations. Some of the estimates, by organizations from the World Bank to the International Applied Systems Analysis in Vienna, suggest that the sums needed would be as high as $1.7 or even $2.2 trillion per year.[22]

Country Commitments for Action

Prior to the COP-21, 186 delegations had submitted their NDCs to the UNFCCC. Because these commitments were made on a voluntary basis, there are discrepancies in the approaches adopted by different countries. Some countries have chosen their baseline year as 2005, and others as 1990 (which was the baseline of the Kyoto Protocol), and calculate their future emissions with reference to that baseline. Other countries have calculated their future emissions compared to what they would have been emitting in a business-as-usual (BAU) scenario. Some countries have pledged reductions of CO_2 emissions in absolute terms, i.e., reductions in actual volumes of emissions, and others in relative terms, or reductions in **carbon intensity** (carbon emissions per unit of GDP).

carbon intensity a measure of carbon emissions per unit of GDP.

Reductions in carbon intensity partly "decouple" emissions from growth, but overall emissions can still increase with economic growth. This option has generally been chosen by developing countries, including the biggest ones, such as China and India, as they are unwilling to commit to measures that would slow down their economic growth. They seek an increasing decoupling between economic growth and the growth of CO_2 emissions, but in the meantime CO_2 emissions will continue to grow in most of these countries. This introduces the important idea of "peaking" emissions in developing countries—allowing total emissions to grow only for a specific period, after which they must decline. China has committed to peaking emissions by 2030.

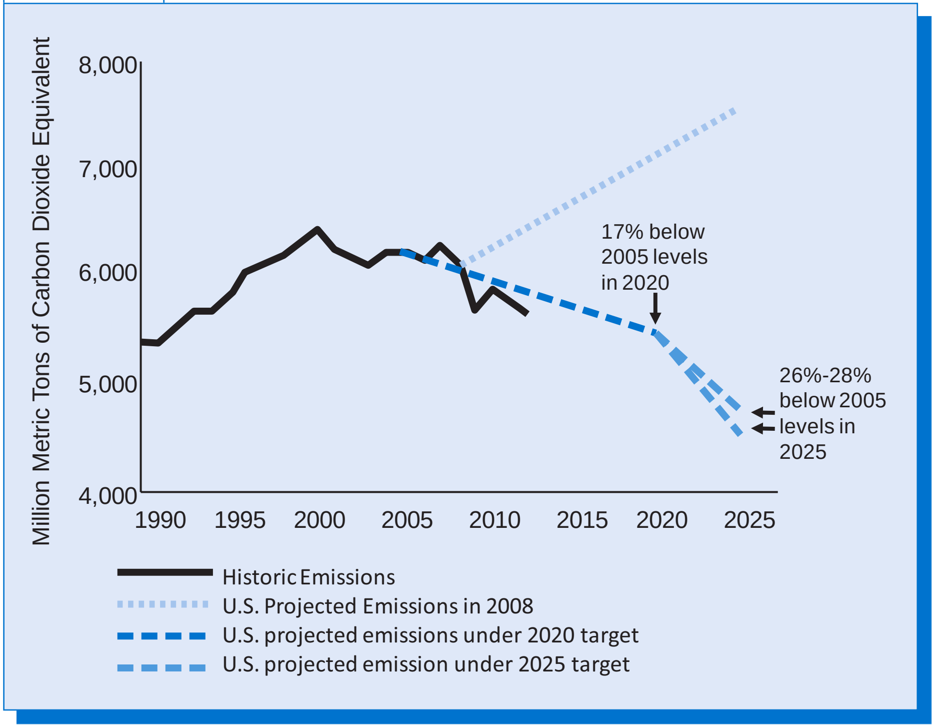
Commitments of Major Emitters

The NDC submitted in March 2015 by the U.S. to the UNFCCC states that "the United States intends to achieve an economy-wide target of reducing its greenhouse gas emissions by 26–28 per cent below its 2005 level in 2025 and to make best efforts to reduce its emissions by 28%."[23] Stated U.S. emissions targets are shown in Figure 13.8. These would continue and accelerate a declining trend already evident in actual U.S. emissions. With an unsympathetic Congress blocking any attempt to pass a climate policy bill, the Obama Administration pursued its climate agenda using administrative action. In August 2015, the United States announced the Clean Power Plan, which aims to reduce CO_2 emissions from the power sector to 32 percent below 2005 levels by 2030.[24] In March 2017, however, President Trump signed an executive order to repeal the Clean Power Plan, throwing U.S. climate actions into doubt—although it is still possible that U.S. emissions could decline based on state policies and market developments (see, for example, discussion of the Northeast and California commitments in the section on "Regional, National, and Local Actions" below).

China's official commitment includes:

- Peaking carbon dioxide emissions by around 2030 and making best efforts to peak earlier.
- Lowering carbon intensity (carbon dioxide emissions per unit of GDP) by 60 percent to 65 percent from the 2005 level.
- Increasing the share of non-fossil fuels in primary energy consumption to around 20 percent.
- Increasing forest stock volume by around 4.5 billion cubic meters above the 2005 level.[25]

Figure 13.8 U.S. Emissions Targets



Source: U.N. Framework Convention on Climate Change, http://unfccc.int/2860.php.

The European Union and its Member States are committed to a binding target of reducing greenhouse gas emissions at least 40 percent by 2030 compared to 1990.

> The EU and its Member States have already reduced their emissions by around 19% [relative to] 1990 levels while GDP has grown by more than 44% over the same period. As a result, average per capita emissions across the EU and its Member States have fallen from 12 tonnes CO_2-eq. in 1990 to 9 tonnes CO_2-eq. in 2012 and are projected to fall to around 6 tonnes CO_2-eq. in 2030.[26]

Commitments by the U.S., China, the E.U. and other major emitters are shown in Table 13.4. Despite the U.S. retreat from its commitment, China and the EU have indicated firm resolve to accomplish their carbon limitation and reduction plans.

How adequate or inadequate are the commitments?

An independent organization, Climate Action Tracker, provides assessments and ratings of submitted NDCs. According to its grading system, the USA is rated "medium" for its commitment, China is rated as "medium with inadequate carbon intensity target," and the European Union is also rated as "medium." The Climate Action Tracker has rated as "inadequate" the commitments of a long list of countries, including Russia, Japan, Australia, New Zealand, Canada, Argentina, South Africa, Chile, and Turkey.[27]

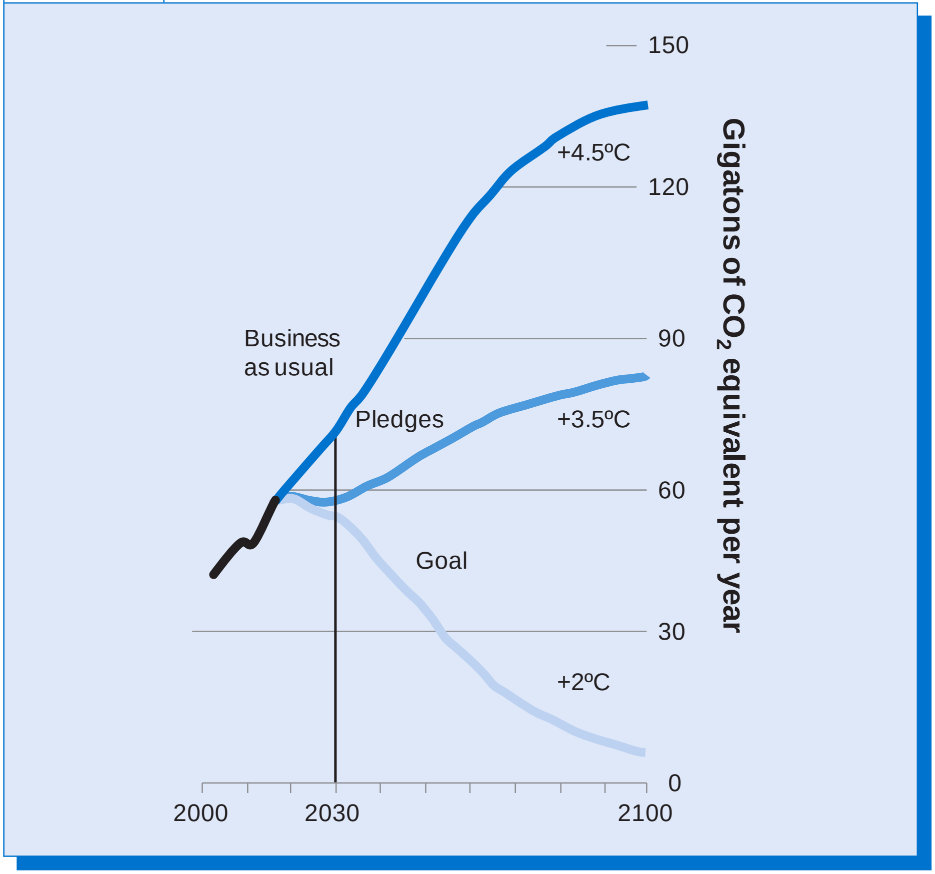
Figure 13.9 shows the differences between a business-as-usual emissions trajectory, the trajectory that would result from the current aggregation of NDCs commitments, and the

Table 13.4 National Commitments by Major Emitters

	Base Level	Reduction Target	Target Year	Land-Use Inclusion/Accounting Method:
China	2005	Emissions peaking 60-65% (carbon intensity)	2030 (or before)	Target to increase forest stock volume by around 4.5 billion cubic meters
United States	2005	26-28%	2025	"Net-net" approach including land use emissions and removals
EU	1990	40%	2030	Policy on land-use accounting to be decided prior to 2020
India	2005	33-35% (carbon intensity)	2030	Not specified
Russia	1990	25-30%	2030	Target depends on the "maximum absorption capacity of forests"
Japan	2013	26%	2030	Forest and agricultural sectors are accounted for using approaches similar to those under the Kyoto Protocol

Source: www.c2es.org/indc-comparison.

Figure 13.9 Business-As-Usual, Paris Pledges, and 2°C Path



Source: http://www.nytimes.com/interactive/2015/11/23/world/carbon-pledges.html?_r=1.

Note: 2°C = 3.6°F; 3.5°C = 6.3°F; 2 4.5°C = 8.1°F.

path that would be necessary to reach 2°C (3.6°F) or less. Most current pledges do not extend beyond 2030, which is why emissions start to rise again after 2030 in Figure 13.9. Considerable strengthening of the pledges would clearly be needed before that date to keep overall emissions on a 2°C track—let alone 1.5°C.[28] According to analysis by the Climate Action Tracker, if policies of comparable strength to those in the current NDCs were maintained after 2030, they would lead to a median warming of about 2.7°C (4.8°F) by 2100—better than the 3.5°C (6.3°F) shown in Figure 13.9, but still far exceeding the Paris targets.[29] (For a scientific perspective on the importance of reaching a 2°C or even 1.5°C target, see Box 13.3.)

To see what is required to achieve a 2°C or 1.5°C target, the concept of a **global carbon budget** is useful. A global carbon budget attempts to quantify the cumulative emissions of carbon that can be added to the atmosphere without exceeding specified temperature increases. To reach a 2°C target, it is necessary to keep within a cumulative global carbon

global carbon budget the concept that total cumulative emissions of carbon must be limited to a fixed amount in order to avoid catastrophic consequences of global climate change.

Box 13.3
THE SCIENTIFIC BASIS FOR THE PARIS CLIMATE TARGETS

The Paris Agreement codified a goal of no more than 2°C of temperature increase, with a more ambitious goal of no more than 1.5°C. What is the reason for these targets? A 2016 study argues that the temperature targets selected in Paris are the scientifically correct ones by comparing these targets to the probability that various catastrophic and irreversible losses will occur, such as the loss of alpine glaciers or the loss of the Amazon rainforest. The authors assessed the available research to determine the temperature range at which each impact is expected to occur. This is shown in Figure 13.10.

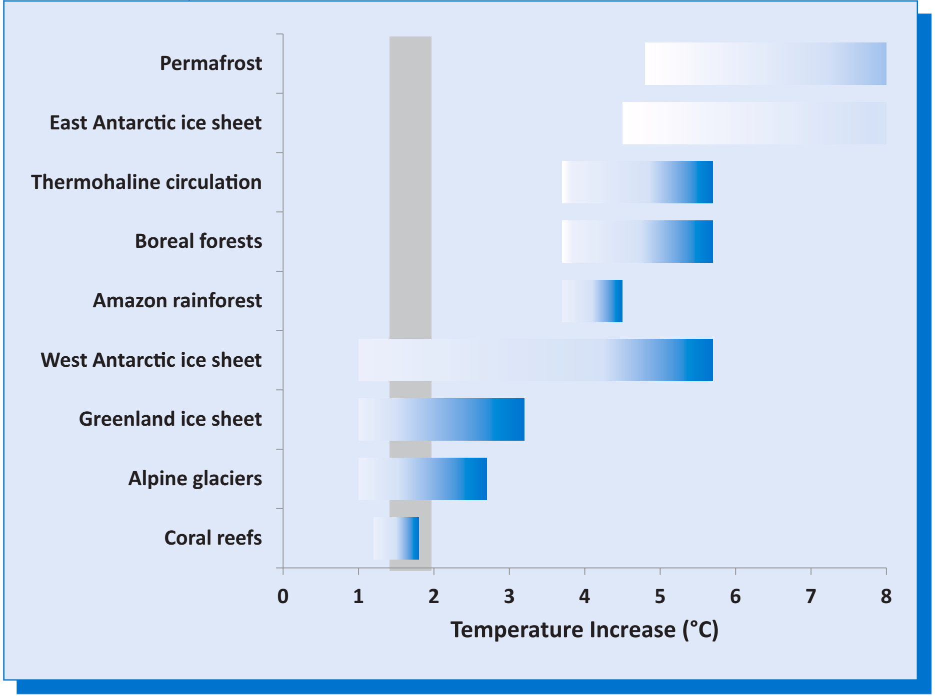
The bar for each impact reflects scientific uncertainty about how much temperatures must increase to make that impact inevitable. The darker the shading, the higher the probability the impact will occur. So, for example, if global average temperatures increase only 1°C there is a small probability alpine glaciers will be lost. But if temperatures increase more than 2.5°C it is nearly certain that alpine glaciers will be lost based on the current research.

The vertical bar represents the range of the Paris climate targets, from 1.5°C to 2°C. Comparing these targets to the various impacts, we see that limiting the temperature increase to 1.5°C offers a chance that the world's coral reefs will not be lost. But at 2°C it is virtually certain that coral reefs will not survive. If the 2°C target can be met, the outlook is better for avoiding the loss of alpine glaciers, the Greenland ice sheet, and the West Antarctic ice sheet, although considerable uncertainty remains. At 4–6°C the Amazon and boreal forests, the East Antarctic ice sheet, and permafrost are all endangered, as is the thermohaline circulation in the oceans, including the Gulf Stream, which keeps much of Europe relatively temperate despite high latitudes. The article concludes that achieving the Paris targets, while ambitious, is therefore essential:

> Beyond 2°C the course would be set for a complete deglaciation of the Northern Hemisphere, threatening the survival of many coastal cities and island nations. Global food supply would be jeopardized by novel extreme-event regimes, and major ecosystems such as coral reefs forced into extinction. Yet, staying within the Paris target range, the overall Earth system dynamics would remain largely intact. Progressing [further] on the other hand, with global warming reaching 3–5°C, would seriously [risk most impacts]. For warming levels beyond this range, the world as we know it would be bound to disappear.

Source: Schellnhuber *et al.*, 2016.

Figure 13.10 The Paris Climate Targets and Catastrophic Global Impacts



Source: Schellnhuber *et al.*, 2016.

Note: The vertical bar represents the range of the Paris climate targets, from 1.5°C to 2.0°C.

budget of no more than 270 additional gigatons of carbon—about 30 years of emissions at current levels. To reach the 1.5°C target, the budget would have to be a mere 110 gigatons—about 12 years of emissions at current rates.[30] The current Paris commitments are inadequate to meet these goals without a significant strengthening of the commitments in future rounds of negotiation.

Regional, National, and Local Actions

While international efforts to establish a framework for emissions reduction have continued, policies have been implemented at regional, national, and local levels. These include:

- To help it meet its obligations under the Kyoto Protocol, the European Union set up a carbon trading system that went into effect in 2005 (see Box 13.4).
- Carbon trading systems have also been established in several regions in the United States. The Regional Greenhouse Gas Initiative (RGGI) is a cap-and-trade program for emissions from power plants in nine Northeastern states. Permits are mostly auctioned off (some are sold at a fixed price), with the proceeds used to fund investments in clean energy and energy efficiency. Permit auction prices have ranged from about \$2 to \$5 per ton of CO_2.[31] In 2013, California initiated a legally binding cap-and-trade

scheme. "The program imposes a greenhouse gas emission limit that will decrease by two percent each year through 2015, and by three percent annually from 2015 through 2020."[32]

- Carbon taxes have been instituted in several countries, including a nationwide tax on coal in India (about $1 per ton, enacted in 2010), a tax on new vehicles based on their carbon emissions in South Africa (also enacted in 2010), a carbon tax on fuels in Costa Rica (enacted in 1997), and local carbon taxes in the Canadian provinces of Quebec, Alberta, and British Columbia (see Box 13.5).

- Networks of cities have also organized to address climate change. The C40 network of megacities, representing 25 percent of global GDP, has focused on measuring and reducing urban emissions. Another network, the Compact of Mayors, a global coalition of over 500 cities, was launched in 2014 with similar goals.[33] By 2050, between 65 percent and 75 percent of the world population is projected to be living in cities, with more than 40 million people moving to cities each year. Urban population will grow from approximately 3.5 billion people now to 6.5 billion by 2050. Estimates suggest that cities are responsible for 75 percent of global CO_2 emissions, with transport and buildings being among the largest contributors.[34]

Box 13.4

THE EUROPEAN UNION CARBON TRADING SYSTEM

In 2005 the European Union (EU) launched its Emissions Trading Scheme (EU-ETS), which covers more than 11,000 facilities that collectively emit nearly half the EU's carbon emissions. In 2012 the system was expanded to cover the aviation sector, including incoming flights from outside the EU. Under the EU-ETS, each country develops a national allocation plan to determine the overall number of permits available. Permits are both auctioned off and allocated to some firms for free based on historical emissions. Any unneeded permits can be sold on the open market.

The initial phase (2005–2007) of the EU-ETS produced disappointing results as permits were over-allocated, leading to a drop in the permit price from more than €30 per tonne to less than €1 by the end of 2007. In the second phase (2008–2012), fewer permits were initially allocated, leading to relatively stable prices of around €15–€20 per tonne for a few years. But by mid-2012 prices had fallen to €5–€10 per tonne as the market again experienced a glut of permits. Despite the volatility in prices, according to the EU the EU-ETS led to a reduction in emissions from large emitters of 8 percent between 2005 and 2010. Also, the costs of the EU-ETS have been less than expected, around 0.5 percent of European gross domestic product (GDP).

The EU has moved into the third phase of the ETS, covering 2013–2020. This phase will require more of the permits to be auctioned, include more greenhouse gases, and set an overall EU cap rather than allowing individual countries to determine their own cap. By the end of the third phase, the program's goal is to reduce overall EU emissions 21 percent relative to 1990 levels, with a further goal of a 43 percent reduction by 2030.

Sources: EU-ETS, http://ec.europa.eu/clima/policies/ets/index_en.htm; Grubb *et al.*, 2009.

Box 13.5
BRITISH COLUMBIA'S CARBON TAX: A SUCCESS STORY

In 2008 the Canadian province of British Columbia, on the Pacific Coast, implemented a carbon tax of $10 per ton of CO_2 (Canadian dollars). The tax rose incrementally by $5 each subsequent year, until it reached $30 in 2012. This translates into an additional 26 cents per gallon of gasoline at the pump, with comparable price increases in other carbon-based energy sources.

The carbon tax is revenue neutral, meaning that the province has cut income and corporate taxes to offset the revenue it gets from taxing carbon. British Columbia now has the lowest personal income tax rate in Canada, and one of the lowest corporate rates among developed countries.

In the first six years of its implementation, consumption of fuels dropped by between 5 percent and 15 percent in B.C., while it rose by about 3 percent in the rest of Canada. During that time, GDP per capita continued to grow in British Columbia, at a slightly higher pace than for the rest of Canada. By lowering taxes on income and corporations, this policy encouraged employment and investment, while discouraging carbon pollution.

British Columbia's experience has been heralded by the OECD and the World Bank as a successful example to follow. A recent study found that the tax had negligible effects on the economy, and had overcome initial opposition to gain general public support. As of 2016, the Canadian government planned to extend the tax to the whole of Canada.

Sources: The World Bank, "Development in a Changing Climate. British Columbia's Carbon Tax Shift: An Environmental And Economic Success," Sept. 10, 2014; *The Economist*, "British Columbia's Carbon Tax: The Evidence Mounts," July 31, 2014; Ministry of Finance, British Columbia, "Carbon Tax: Overview of the Revenue-Neutral Carbon Tax,"; Murray and Rivers, 2015; Metcalf, 2015; http://www.nationalobserver.com/2016/10/03/news/breaking-feds-announce-pan-canadian-carbon-price-plan-2018.

Forests and Soils

While the major focus of climate policy has been on the reduction of emissions from carbon-based fuels, the role of forests and soils is also crucial. Currently about 11 percent of greenhouse gas emissions come from forest and land use change, especially tropical forest loss.[35] International negotiations have also led to the adoption of a program known as **REDD (Reduction of Emissions from Deforestation and Degradation)**. The Copenhagen Accord (2009) acknowledged the need to act on reducing emissions from deforestation and forest degradation and established a mechanism known as REDD-plus. The Accord emphasizes funding for developing countries to enable action on mitigation, including substantial finance for REDD-plus, adaptation, technology development and transfer, and capacity building (discussed further in Chapter 19).

Reduction of Emissions from Deforestation and Degradation (REDD) a United Nations program adopted as part of the Kyoto process of climate negotiations, intended to reduce emissions from deforestation and land degradation through providing funding for forest conservation and sustainable land use.

In addition to reducing emissions, forests and soils have huge potential for absorbing and storing carbon. The Earth's soils store 2,500 billion tons of carbon—more carbon than the atmosphere (780 billion tons) and plants (560 billion tons) combined. But it is estimated that soils have been depleted of 50 to 70 percent of their natural carbon in the last century. Globally, those depleted soils could reabsorb 80 to 100 billion metric tons of carbon per year, through regenerative agriculture, including polyculture, cover cropping, agroforestry, nutrient recycling, crop rotation, proper pasture management, and organic soil amendments like compost and biochar (discussed further in Chapter 16).[36] It is likely that this vast unexploited potential for carbon storage will be a major focus of future climate policy—a crucial factor in the effort to move from the intermediate "pledges" path in Figure 13.9 to the "goals" path necessary to hold global temperature change to no more than 2°C.

13.5 OTHER ECONOMIC POLICY PROPOSALS: ENVIRONMENT AND EQUITY

In the final section of this chapter, we take a look at proposals for balancing carbon reduction with equity issues on a national and international scale. While these policies have not yet been implemented on a national or global scale, they provide insight into economic principles that can guide future policymaking.

A Distributionally Neutral Carbon Tax in the United States

Placing a price on carbon emissions in developed countries would result in unequal impacts on households of different income levels. Specifically, a carbon tax would be a **regressive tax**, meaning that as a percentage of income the tax would affect lower-income households more than higher-income households. The reason is that lower-income households spend a higher percentage of their income on carbon-intensive goods, such as gasoline, electricity, and heating fuels. Thus a carbon tax, implemented alone, would increase the overall level of income inequality.

A carbon tax does not necessarily mean that overall taxes must increase. Instead, implementing a carbon tax could be coupled with a decrease in one or more existing taxes such that the overall amount of taxes paid by the average household stays the same. Thus a carbon tax could be revenue neutral, meaning that the overall amount of tax revenue collected by the government is unchanged.

The distributional impacts will depend on which tax is reduced. Some taxes are regressive, affecting lower-income households more heavily, while other taxes are **progressive taxes**, affecting higher-income households more heavily. Given that a carbon tax is regressive and increases inequality, most proposals for a revenue-neutral carbon tax suggest achieving revenue neutrality by decreasing a regressive tax. In the United States, regressive taxes include sales taxes, the payroll tax, and excise taxes.[37] Could one of these taxes be reduced such that the overall distributional impact of a carbon tax would be relatively constant across income levels?

An economic analysis by Gilbert Metcalf shows that offsetting a carbon tax in the United States with a decrease in the payroll tax could produce a result that is approximately **distributionally neutral**, meaning that the impact on households at different income levels would be nearly the same as a percentage of income.[38]

regressive tax a tax in which the rate of taxation, as a percentage of income, decreases with increasing income levels.

progressive taxes taxes that comprise a higher share of income with higher income levels.

distributionally neutral tax shift a change in the pattern of taxes that leaves the distribution of income unchanged.

Metcalf proposes offsetting the carbon tax by providing a tax credit for a worker's payroll tax up to a maximum credit of $560 per year per individual—an amount that allows the overall effect on taxes to be revenue-neutral. For low-income households, this tax credit is relatively large as a percentage of income (over 2 percent), but for higher-income households this credit is only about 1 percent or less of income. The credit averages from about $200 to over $1,000, depending on household income level. The net effect, considering both the carbon tax and the tax credit, is never more than an average of $135 for any income group. Households in the middle and upper-middle income groups tend to end up slightly ahead, while households in the lowest income groups end up losing slightly. But the overall impact is nearly distributionally neutral. Some further minor adjustments could be instituted to eliminate the slightly negative impact on lower income households. Thus Metcalf's analysis demonstrates that a carbon tax in the United States could achieve carbon reductions without increasing overall taxes or having a disproportionate impact on any income group.

Greenhouse Development Rights

On a global scale, equity issues relate to income differences between countries as well as income distribution within countries. What principles should be used to determine how emissions reductions and financing of mitigation and adaptation costs should be allocated among countries? Various approaches are possible, taking into account fairness, efficiency, and the concept of universally shared rights to the global commons.[39] The **greenhouse development rights (GDR)** framework proposes that only those people living above a certain economic threshold of development should be obliged to address the climate change problem.[40] Those who live below the threshold should instead be allowed to focus on economic growth, without any climate obligations.

greenhouse development rights (GDR) an approach for assigning the responsibility for past greenhouse gas emissions and the capability to respond to climate change.

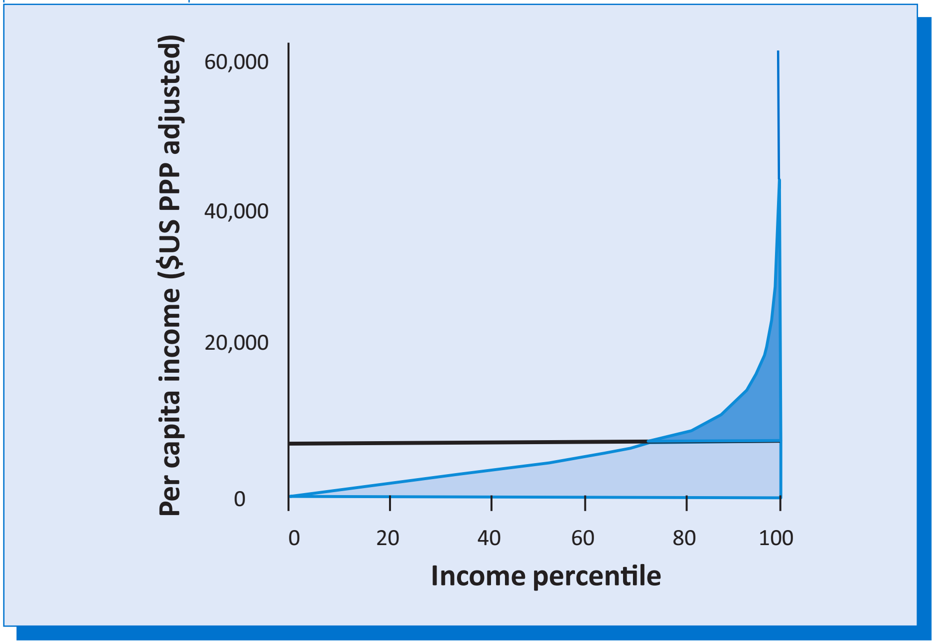
The GDR analysis essentially develops a methodology for assigning each country's obligation to provide financing for an international climate change mitigation and adaptation fund. It considers two factors to determine a country's obligation:

- *Capacity*: The capacity of a country to provide financing is based on its GDP, yet all income below a defined development threshold is excluded. The GDR analysis sets the development threshold at $7,500 per capita, a level that generally allows one to avoid the problems of severe poverty, such as malnutrition, high infant mortality, and low educational attainment. Figure 13.11 illustrates the concept using China as an example. The graph shows the income distribution curve for China, starting with the person with the lowest income and moving to the right as incomes increase. All income below the horizontal line at the $7,500 development threshold is excluded from China's capacity. The area above the development threshold line represents China's total capacity to provide financing for climate change.
- *Responsibility*: The GDR approach defines responsibility for greenhouse gas emissions as a country's cumulative emissions since 1990, the same baseline year used for the Kyoto Protocol. As with capacity, emissions associated with consumption below the development threshold are excluded from the responsibility calculation. Each country's share of the global responsibility would be calculated by dividing its cumulative emissions by the global total.

The results indicate each country's share of the global capacity and responsibility. Then, a responsibility-capacity index (RCI) is calculated as the unweighted average of the two values. The RCI represents each country's obligation for financing a response to climate change.

The results for selected countries and country groups are presented in Table 13.5. The United States, which has by far the greatest cumulative responsibility for emissions, would be allocated one-third of the global bill for addressing climate change. The European Union

Figure 13.11 Climate Change Capacity for China, Greenhouse Development Rights Framework



Source: Baer *et al.*, 2008.

Note: PPP = purchasing power parity.

would receive more than one-quarter of the bill. Japan would be asked to finance about 8 percent of the response, China about 6 percent, and Russia about 4 percent. The least developed countries are collectively asked to pay a negligible share of the global bill. These shares would change over time, as developing countries' share of global emissions increases and their capacity to respond (assuming successful development) increases also.

Table 13.5 **Responsibility Capacity Indices, Greenhouse Development Rights Framework, Selected Countries/Regions** (Percent of Global Total)

Country or Group	Population	Capacity	Responsibility	RCI
United States	4.5	29.7	36.4	33.1
EU-27	7.3	28.8	22.6	25.7
Japan	1.9	8.3	7.3	7.8
China	19.7	5.8	5.2	5.5
Russia	2.0	2.7	4.9	3.8
Brazil	2.9	2.3	1.1	1.7
Mexico	1.6	1.8	1.4	1.6
South Africa	0.7	0.6	1.3	1.0
India	17.2	0.7	0.3	0.5
Least-developed countries	11.7	0.1	0.04	0.1

Source: Baer *et al.*, 2007.

Box 13.6
FOR U.S. COASTAL CITIES, CLIMATE ADAPTATION STARTS NOW

In August 2016, torrential downpours along the Gulf Coast led to deadly floods in Southern Louisiana. With $9 billion in estimated damages, this natural catastrophe qualified as the worst in the United States since Hurricane Sandy in October 2012.

Linking such “off-the-charts” episodes to climate disruption is not a simple cause-to-effect relation, but scientists’ models can give orders of magnitude of probabilities for such events. What was considered a once-in-a-thousand-year occurrence is becoming a new reality that coastal regions need to cope with. The National Oceanic and Atmospheric Administration found that global warming increases the chances of such intense rains by 40 percent due to increased moisture in a warmer atmosphere.

Already, coastal cities around the United States are investing massively to prepare for future floods. Fort Lauderdale, Florida, is spending millions of dollars fixing battered roads and drains damaged by increasing tidal flooding. Miami Beach increased local fees to finance a $400 million plan that includes raising streets, installing pumps, and elevating sea walls. The cost of adapting to rising seas for the medium-size town of Norfolk, Virginia, has been estimated at about $1.2 billion, or about $5,000 for every resident.

These costs for individual cities imply that the order of magnitude of costs for the whole East Coast and Gulf Coast will be several trillions. 1.9 million shoreline homes worth a combined $882 billion might be lost to rising sea levels by 2100. According to some economic analysts, the possibility of a collapse in the coastal real estate market could rival the impacts of the dot-com and real estate crashes of 2000 and 2008. The Pentagon, too, faces major adaptation issues, as many naval bases are facing serious threats and their land is at risk of disappearing within this century.

Sources: Jonah Engel Bromwich, “Flooding in the South Looks a lot Like Climate Change,” *New York Times*, August 16, 2016; Henry Fountain, “Scientists See Push From Climate Change in Louisiana Flooding,” *New York Times*, September 7, 2016; Justin Willis, “Flooding of Coast, Caused by Global Warming, Has Already Begun,” *New York Times*, September 3, 2016; Ian Urbina, “Perils of Climate Change Could Swamp Coastal Real Estate,” *New York Times*, November 24, 2016.

climate justice equitable sharing both of the burdens of climate change and the costs of policy responses.

Following the principles suggested by the GDR proposal would be consistent with the principle of **climate justice** but would necessitate a substantial increase in the commitments of developed nations, well beyond the $100 billion included in the Paris agreement. According to the authors of the GDR proposal:

> For a fully equitable climate agreement, substantial public funds for mitigation must be delivered. . . . As a supplement to their domestic NDCs, each developed country party should set a target to provide the means of implementation to developing countries to address the emissions reduction gap. Significantly scaled-up public finance for adaptation and to address loss and damage are also imperative.[41]

13.6 CONCLUSION: DIMENSIONS OF CLIMATE CHANGE

Climate change is an issue that embodies many of the analyses discussed in this text, including externalities, common property resources, public goods, renewable and nonrenewable resources, and the discounting of costs and benefits over time. It has economic, scientific, political, and technological dimensions. Economic analysis alone cannot adequately respond to a problem of this scope, but economic theory and policy have much to offer in the search for solutions.

An effective response to the climate change problem requires much more sweeping action on a global scale than anything so far achieved. But whether we are discussing local initiatives or broad global schemes, we cannot avoid the issue of economic analysis. Economic policy instruments that have the power to alter patterns of energy use, industrial development, and income distribution are essential to any plan for mitigating or adapting to climate change. As noted in Chapter 12, evidence of climate change impacts is already clear, and the issue will become more pressing as greenhouse gas accumulation continues and costs of damages and of climate adaptation rise (see Box 13.6). The tools of economic analysis will provide critical insights as the world grapples with this continuing crisis.

Summary

Policies to respond to global climate change can be preventive or adaptive. One of the most widely discussed policies is a carbon tax, which would fall most heavily on fuels that cause the highest carbon emissions. The revenues from such a tax could be recycled to lower taxes elsewhere in the economy, or they could be used to assist people in lower income brackets, who will suffer most from higher costs of energy and goods. Another policy option is tradable carbon emissions permits which can be bought and sold by firms or countries, depending on their level of carbon emissions (also known as "cap-and-trade"). Both of these policies have the advantage of economic efficiency, but it can be difficult to obtain the political support necessary to implement them. Other possible policy measures include shifting subsidies from fossil fuels to renewable energy, strengthening energy efficiency standards, and increasing research and development on alternative energy technologies.

Global carbon emissions could be stabilized by scaling up existing technologies, according to the idea of climate stabilization wedges. The greenhouse gas abatement cost curve indicates that numerous opportunities exist for actions that could reduce carbon emissions and also save households and businesses money, and that billions of tons of additional emissions can be avoided at low cost. One implication of the cost curve is that efficiency standards can be an important complement to a carbon pricing policy.

The Paris Agreement of 2015 replaced the earlier Kyoto Protocol mandating reductions of greenhouse gases by industrialized countries. Unlike Kyoto, which had limited success, the Paris Agreement involves almost all the world's countries, but its provisions are based on voluntary pledges. It creates a framework for substantial reductions by the United States and other industrialized countries, and for reduction of emissions intensity (emissions per unit GDP) by China, India, and other developing countries, with a target date for a "peaking" of emissions by China. A review process is intended to strengthen countries' commitments over time.

In addition to international commitments, many initiatives have been taken at regional, national and local levels, involving carbon taxes, cap-and-trade, and other emission reduction measures. Great potential for additional reductions exists through improving forest and agricultural practices, resulting in less emissions and increased carbon storage in forests and soils.

Well-designed economic analyses can provide potential blueprints for effective and equitable national and international climate change policies. For example, a carbon tax in the United States can be designed to be both revenue- and distributionally neutral.

The "greenhouse development rights" framework proposes allocating the financing for climate change mitigation and adaptation based on each country's responsibility for past emissions and economic capacity, while still allowing poor countries to achieve economic development.

Key Terms and Concepts

adaptive measures

cap-and-trade

carbon footprint

carbon sinks

carbon tax

climate stabilization wedge

cost-benefit analysis

cost-effectiveness analysis

distributionally neutral tax shift

efficiency standards

elasticity of demand

greenhouse development rights (GDR)

global carbon budget

nationally determined contribution (NDC)

pollution taxes

preventive measures

price volatility

progressive taxes

reduction of emissions from deforestation and degradation (REDD)

regressive tax

revenue-neutral tax shift

technology transfer

transferable (tradable) permits

Discussion Questions

1. Which economic climate change policy do you prefer: A carbon tax or a cap-and-trade system? Why? What are the main barriers to effective policy implementation?
2. Climate change policies can focus on changing behaviors or changing technology. Which approach do you think could be more effective? What policies can be used to encourage changes in each?
3. The process for formulating and implementing international agreements on climate change policy has been plagued with disagreements and deadlocks. What are the main reasons for the difficulty in agreeing on specific policy actions? From an economic point of view, what kinds of incentives might be useful to induce countries to enter and carry out agreements? What kinds of "win-win" policies could be devised to overcome negotiating barriers?

Exercises

1. Suppose that under the terms of an international agreement, U.S. CO_2 emissions are to be reduced by 200 million tons and those of Brazil by 50 million tons.

Here are the policy options that the United States and Brazil have to reduce their emissions:

United States:

Policy Options	Total Emissions Reduction (million tons carbon)	Cost ($ billion)
A: Efficient machinery	60	12
B: Reforestation	40	20
C: Replace coal-fueled power plants	120	30

Brazil:

Policy Options	Total Emissions Reduction (million tons carbon)	Cost ($ billion)
A: Efficient machinery	50	20
B: Protection of Amazon forest	30	3
C: Replace coal-fueled power plants	40	8

a) Which policies are most efficient for each country in meeting their reduction targets? How much will be reduced using each option, at what cost, if the two countries must operate independently? Assume that any of the policy options can be partially implemented at a constant marginal cost. For example, the United States could choose to reduce carbon emissions with efficient machinery by 10 million tons at a cost of $2 billion. (Hint: start by calculating the average cost of carbon reduction in dollars per ton for each of the six policies).

b) Suppose a market of transferable permits allows the United States and Brazil to trade permits to emit CO_2. Who has an interest in buying permits? Who has an interest in selling permits? What agreement can be reached between the United States and Brazil so that they can meet the overall emissions reduction target of 250 million tons at the least cost? Can you estimate a range for the price of a permit to emit one ton of carbon? (Hint: use your average cost calculations from the first part of the question.)

2. Suppose that the annual consumption of an average American household is 1,000 gallons of gasoline and 200 Mcf (thousand cubic feet) of natural gas. Using the figures given in Table 13.2 on the effects of a carbon tax, calculate how much an average American household would pay per year with an added tax of $50 per ton of carbon dioxide if there was no initial change in quantity demanded. (Assume that the before-tax market prices remain unchanged.) Then assuming a short-term demand elasticity of –0.1, and a long-term elasticity of –0.5, calculate the reductions in household quantity demanded for oil and gas in the short and long term. If there are 100 million households in the United States, what would be the revenue to the U.S. Treasury of such a carbon tax, in the short and long term? How might the government use such revenues? What would the impact be on the average family? Discuss the difference between the short-term and long-term impacts.

Notes

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7. World Health Organization, 2009; WHO, *Climate Change and Health*, June 2016, http://www.who.int/mediacentre/factsheets/fs266/en/.
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11. Goodwin *et al*., 2004.
12. Carl and Fedor, 2016.
13. Pacala and Socolow, 2004, Socolow and Pacala, 2006; Socolow, 2011.
14. Socolow and Pacala, 2006; Schellnhuber *et al*., 2016.
15. Socolow and Pacala, 2006.
16. McKinsey & Company, 2007 and 2009.
17. Ibid.
18. See Kesicki and Ekins, 2011, for a critique of marginal abatement cost curves.
19. Clark, 2012.
20. Coral Davenport, "Paris Climate Deal Reaches Milestone as 20 More Nations Sign On," *New York Times*, September 21, 2016; Coral Davenport, "Nations, Fighting Powerful Refrigerant that Warms Planet, Reach Landmark Deal," *New York Times*, October 15, 2016.
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26. Ibid.
27. http://climateactiontracker.org/methodology/85/Comparability-of-effort.html.; http://www.wri.org/blog/2015/07/japan-releases-underwhelming-climate-action-commitment.
28. Millar *et al*., 2016.
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30. The Global Carbon Project, "Global Carbon Budget," http://www.globalcarbonproject.org/; Schellnhuber *et al*., 2016.
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32. http://www.c2es.org/us-states-regions/key-legislation/california-cap-trade.
33. http://www.c40.org/; https://www.compactofmayors.org/.
34. http://www.theguardian.com/cities/2015/nov/17/cities-climate-change-problems-solution; http://www.unep.org/urban_environment/issues/climate_change.asp.
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Web Sites

1. **http://www.wri.org/our-work/topics/climate.** World Resource Institute's web site on climate and atmosphere. The site includes numerous articles and case studies.
2. **http://unfccc.int/2860.php.** Homepage for the United Nations Framework Convention on Climate Change. The site provides data on the climate change issue and information about the ongoing process of negotiating international agreements related to climate change.
3. **www.rff.org/research/topics/climate-change.** Publications by Resources for the Future on issues of energy and climate change. The site includes articles on carbon pricing and cap-and-trade in practice, as well as climate adaptation.

CHAPTER

14 Greening the Economy

Chapter 14 Focus Questions

- Is a "green economy" possible?
- What economic theories provide insight into the relationship between the economy and the environment?
- Is protecting the environment bad for the economy?
- What policies can promote a transition to a green economy?

14.1 THE GREEN ECONOMY: INTRODUCTION

Economic and environmental objectives are often presented as conflicting goals. A common theme in political debates in recent years is that certain environmental regulations result in unacceptable job losses. Thus the choice is presented as being between improved environmental quality on one hand, and a robust economy on the other (see Box 14.1 for a recent example of this debate).

But is the choice this simple? Can't we have *both* sufficient environmental quality and plentiful, good jobs? In this chapter we explore the relationship between protecting the environment and economic growth. We'll consider the research on the topic to determine if there is necessarily a tradeoff between the environment and the economy. While protecting the environment clearly involves some costs, including job losses in some sectors, economists focus on whether the benefits justify these costs. Environmental regulations may also create jobs in some sectors—for example, environmental restrictions on coal plants may lead to expansion of wind power production. Thus it may be possible that at least some environmental regulations actually lead to net job gains. This is an important issue in analyzing polices to combat climate change, since, as we have seen in previous chapters, responding to climate change will require extensive changes in energy production and other sectors of the economy.

Some recent policy proposals suggest that a well-designed response to current environmental and energy challenges can actually be the engine for future economic development. Companies and countries that make the investments necessary to create a low-environmental-impact society may gain a competitive advantage over those that continue to pursue business as usual. In addition, excessive rates of natural capital degradation can reduce economic productivity, measured in traditional terms as a reduction in GDP, or in broader terms using the measures we discussed in Chapter 10. Thus maintaining natural capital may be a critical factor to ensure future economic growth.

> **green economy** an economy that improves human well-being and social equity, while reducing environmental impacts.

A more ambitious goal is to create a new "**green economy**" that embodies the concept of sustainable development. The United Nations Environment Program (UNEP) has defined a green economy as:

> [O]ne that results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities. In its simplest expression, a green economy can be thought of as one which is low carbon, resource efficient and socially inclusive.
>
> [In] a green economy, growth in income and employment is driven by public and private investments that reduce carbon emissions and pollution, enhance energy and resource efficiency, and prevent the loss of biodiversity and ecosystem services. These investments need to be catalyzed and supported by targeted public expenditure, policy reforms and regulation changes. This development path should maintain, enhance and, where necessary, rebuild natural capital as a critical economic asset and source of public benefits, especially for poor people whose livelihoods and security depend strongly on nature.[1]

Box 14.1
DEBATE OVER THE KEYSTONE XL PIPELINE

The Keystone XL pipeline was proposed in 2008 by the TransCanada Corporation to transport oil from Alberta to Nebraska. For several years, the pipeline became a divisive political issue, often presented as a choice between job creation and environmental quality.

Proponents of the pipeline argued that it would provide access to a new source of energy while creating a significant number of jobs. According to TransCanada's CEO in 2014, the pipeline would create 42,000 direct and indirect "ongoing, enduring jobs." While this estimate came from a 2014 environmental impact statement (EIS) by the U.S. Department of State, the EIS noted that the jobs would only last during a one-year construction phase, and that only about 3,900 of these jobs would be direct construction jobs. Once the pipeline was completed, the EIS estimated that it would support just 35 permanent jobs.

In addition to the small number of permanent jobs created, opponents of the pipeline stated that it would pose a risk of oil spills while tapping into a particularly dirty source of energy as much of the oil would come from Canadian tar sands, which have higher carbon emissions per barrel as well as destructive local environmental impacts on forest and water ecosystems. In a 2015 letter to the State Department, the U.S. Environmental Protection Agency warned that building the pipeline would result in an increase in "greenhouse gas emissions, over what would otherwise occur."

In early 2015 both the U.S. Senate and House voted to approve the pipeline, but President Obama vetoed the project, citing that it would not be "a silver bullet for the economy" and would undermine America's "global leadership" on the issue of climate change. In January 2017, President Trump reversed this veto, clearing the way for development of the pipeline, but economic issues such as falling oil prices, as well as continued local opposition still left the ultimate fate of the pipeline unclear.

Sources: http://www.politifact.com/punditfact/statements/2014/nov/16/russ-girling/transcanada-ceo-says-42000-keystone-xl-pipeline-jo/; https://keystonepipeline-xl.state.gov/; Peter Baker and Coral Davenport, "Trump Revives Keystone Pipeline Rejected by Obama," *New York Times* January 24, 2017.

Note that the concept of a green economy does not necessarily reject economic growth, but instead seeks to foster growth that is compatible with sustainability. It explicitly rejects the standard jobs versus the environment choice:

> Perhaps the most widespread myth is that there is an inescapable trade-off between environmental sustainability and economic progress. There is now substantial evidence that the "greening" of economies neither inhibits wealth creation nor employment opportunities, and that there are many green sectors which show significant opportunities for investment and related growth in wealth and jobs.[2]

In addition to environmental sustainability, the green economy should promote social equity. Thus advocates of a green economy reject the notion that sustainability must limit the economic aspirations of the world's developing countries.

Later in the chapter we'll discuss specific policy proposals to transition to a green economy, some of which build on policies mentioned in earlier chapters, such as removing fossil fuel subsidies and internalizing externalities. We'll also look at some empirical analysis that compares the economic and environmental performance of the green economy to a business-as-usual scenario. But first we discuss economic theories of the relationship between the economy and the environment.

14.2 THE RELATIONSHIP BETWEEN THE ECONOMY AND THE ENVIRONMENT

We can study the relationship between the economy and the environment in both directions. We can look at how environmental protection impacts economic performance, and we can look at how economic growth impacts environmental quality. In this chapter we will consider both perspectives.

Environmental Kuznets Curves

First, let's consider how economic growth impacts environmental quality. Specifically, as a nation gets richer over time, how will this affect its environmental quality? The answer isn't obvious. On one hand, a richer nation is likely to use more resources, demand more energy, and produce more waste and pollution. On the other hand, a richer nation can afford to invest in renewable energy, install state-of-the-art pollution control equipment, and implement effective environmental policies.

In economic terms, it is widely accepted that environmental quality is a **normal good**—meaning that people will seek to "purchase" more of it as their income increases. What is more debatable is whether environmental quality is also a **luxury good**—meaning that spending on it increases disproportionately as income grows. It may be that environmental quality is a luxury good over some income levels, and merely a normal good at other income levels.[3]

normal good a good for which total expenditures tend to increase as income increases.

luxury good a good that people tend to spend a higher percentage of their income on as their incomes increase.

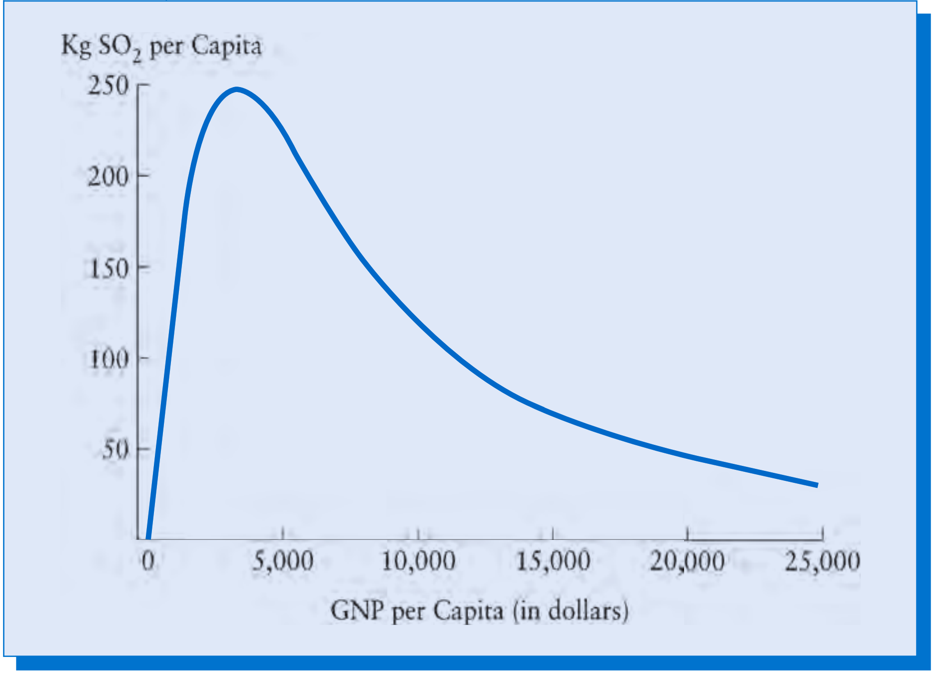
An appealing hypothesis is that economic growth will eventually provide a nation with the resources to reduce its environmental impacts. As a 1992 paper argued:

> [T]here is clear evidence that, although economic growth usually leads to environmental deterioration in the early stages of the process, in the end the best—and probably the only—way to attain a decent environment in most countries is to become rich.[4]

This notion that environmental impacts tend to increase initially as a country becomes richer, but then eventually decrease with further income gains, has become known as the **environmental Kuznets curve (EKC)** hypothesis.[5] This hypothesis proposes that the relationship between income and environmental impacts is an inverted-U shape. The concept is illustrated in Figure 14.1, based on actual data on sulfur dioxide emissions from the 1980s. We see that per-capita SO_2 emissions increase with income up to a per-capita income of around \$4,000. But above that income level, SO_2 emissions per capita decline steadily. This is an encouraging result because the "turning point" occurs at a relatively modest income level. Thus a moderate amount of economic growth can lead to substantial SO_2 emission reductions. The validity of an environmental Kuznets curve for SO_2 emissions was further tested in a 2015 paper, which found evidence for the inverted-U relationship in 19 of 25 OECD countries tested, based on data from 1950–2005.[6]

environmental Kuznets Curve (EKC) the theory that a country's environmental impacts increase in the early stages of economic development but eventually decrease above a certain level of income.

Figure 14.1 **Environmental Kuznets Curve for Sulfur Dioxide Emissions**



Source: Adapted from Panayotou, 1993.

Note: GNP = gross national product; kg = kilogram; SO_2 = sulfur dioxide.

While the EKC hypothesis seems to apply to SO_2, further analysis indicates that it does not apply to all environmental impacts. Perhaps most importantly, the EKC hypothesis does not match the data on carbon dioxide emissions, the primary cause of human-induced climate change. Figure 14.2 illustrates this finding. Statistically, an attempt to fit an inverted-U trendline through the data for 2013 shows that there is no turning point—per-capita CO_2 emissions continue to rise as per-capita income increases.[7] A more sophisticated statistical analysis in 2009 tested the EKC hypothesis for carbon emissions and concluded that "despite these new [statistical] approaches, there is still no clear-cut evidence supporting the existence of the EKC for carbon emissions."[8] A 2015 analysis reached the same conclusion—that "it is evident that for OECD countries rising income is associated with an increase in [CO_2] emissions. No income turning points are found for the observed sample of countries."[9] Thus promoting economic growth does not appear to be a means to address the issue of global climate change.

The EKC hypothesis has been tested for numerous other environmental impacts. While the theory has been supported in some analyses of municipal solid waste[10] and some local air pollutants such as SO_2, carbon monoxide, and nitrogen oxides,[11] it does not seem to apply more broadly to other environmental impacts. A 2015 paper testing the EKC hypothesis using a dataset of 47 countries concludes that:

> Overall, our findings do not lend strong support to the presumed EKC-typed relationship. . . . At best the relationship between economic growth and environmental quality is shown to be typified by an N-shaped curve—indicating that any delinking of economic growth from environmental quality is temporal. An important policy issue arising from here is

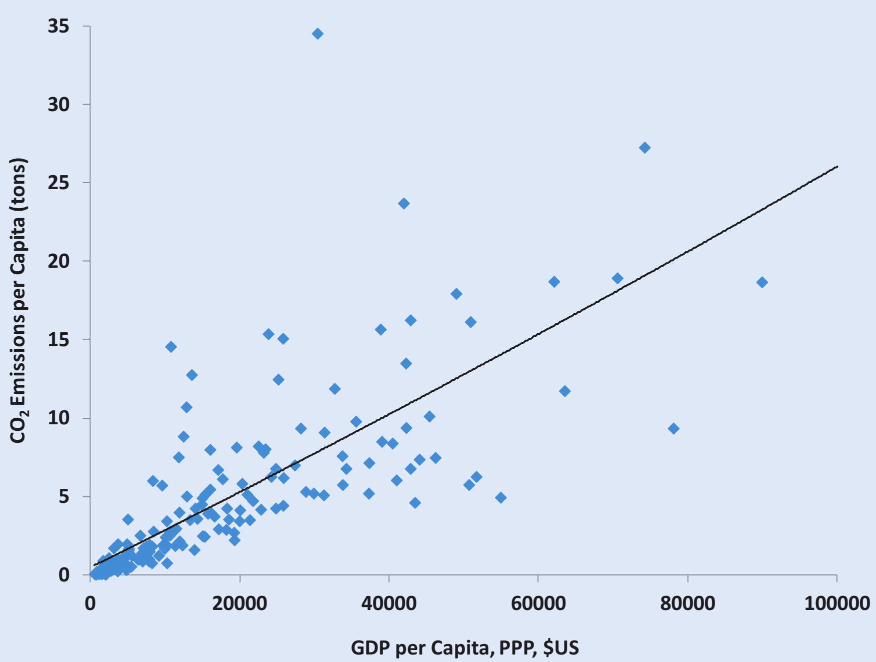
that as nations (especially developing countries) continue to demand more energy to drive their growth process, adequate concern should be giving to environmental impacts of such process. The evidence in this paper suggests that it would be misleading to follow the policy of polluting first and cleaning later as espoused by proponents of EKC. It does not make much sense to "do nothing" and wait for the magic-wand of economic growth to cure environmental problems. Proactive policies and measures are required to mitigate the problem.[12]

The Porter Hypothesis and the Costs of Environmental Regulation

Another hypothesis looks at the interaction between the economy and environment in the opposite direction. Traditional economic theory indicates that firms minimize their costs in order to remain competitive. Thus any environmental regulation imposes an additional cost to firms, and thus reduces their profits. This doesn't mean that the benefits of environmental regulations can't outweigh these costs, but that firms will end up worse off as a result of environmental regulations.

This notion was challenged in a 1995 paper that suggested that the key to competitiveness, whether it be for a firm or a nation, rests in continual innovation.[13] Well-designed

Figure 14.2 Per Capita GDP and Carbon Dioxide Emissions, 2013



Source: Carbon emissions data from Carbon Dioxide Information Analysis Center (CDIAC) and GDP data from World Bank, World Development Indicators database.

Note: CO_2 = carbon dioxide; GDP = gross domestic product; PPP = purchasing power parity. Data points indicate individual countries' GDP per capita and CO_2 emissions per capita in 2013.

environmental regulations provide an impetus for innovation, and thus can actually lower costs and provide a competitive advantage.

> In short, firms can actually benefit from properly crafted environmental regulations that are more stringent (or are imposed earlier) than those faced by their competitors in other countries. By stimulating innovation, strict environmental regulations can actually enhance competitiveness.[14]

The idea that environmental regulation can lead to lower costs for firms has become known as the **Porter hypothesis**. Like the EKC hypothesis, the Porter hypothesis is controversial. The main reason is that it contradicts the common economic assumption that firms minimize costs. If such cost-saving innovations were available, then standard economic theory would suggest that firms would pursue such options without the spur of regulation. But the Porter hypothesis notes that firms may not be focused on ways to reduce environmental impacts, thus missing potential cost-saving innovations. Regulations may make firms more aware of new technologies and direct investments into new areas of research.

> **Porter hypothesis** the theory that environmental regulations motivate firms to identify cost-saving innovations that otherwise would not have been implemented.

The Porter hypothesis was never intended to apply to all environmental regulations. Obviously some regulations do impose net costs on firms, even after technological innovations are implemented. Numerous studies have explored the validity of the Porter hypothesis. Similar to the studies of the EKC hypothesis, the results are mixed. Some analyses have studied the Porter hypothesis by looking at firm-level data within a country. For example, a firm-level study in India found evidence of the Porter hypothesis among water-polluting firms. Those firms with the lowest levels of water pollution also performed the best economically.[15] A 2015 analysis of the chemical manufacturing industry in the United States also supported the Porter hypothesis.[16] The study found that those firms with stricter limits on their allowable levels of water pollution also had higher profits as a percentage of their total sales. But other firm-level research fails to support the Porter hypothesis. A 2013 study in Sweden found that those firms with the largest investments in environmental protection tend to be less efficient than average, particularly in the highly-regulated pulp and paper industry.[17]

Other analyses have tested whether nations with more stringent environmental regulations gain an advantage in terms of international trade. The results generally don't support the Porter hypothesis at a national level. A 2011 study based on data from over 4,000 facilities in seven developed nations found that environmental regulation does induce innovations but that the net effect of regulations is still negative (i.e., they impose net costs on firms).[18] Another analysis based on data from 71 countries found evidence that countries with lax environmental regulations lead to competitive advantages in some industries, particularly in the minerals sector, but not all industries.[19]

A 2014 paper summarizing the existing research on the Porter hypothesis at both the firm- and national-levels concludes that the:

> [e]mpirical research on the [Porter hypothesis] is largely inconclusive. Results are usually very context-specific and hence can only provide limited general policy conclusions—raising the question to what extent the results from a specific policy change, aimed at a particular pollutant and industry in a given country, can be generalised.[20]

This finding is echoed by another 2014 paper which states that "[o]ne possible reason for mixed evidence in more than 20 years of empirical research on the Porter hypothesis could simply be that different types of environmental innovation with different effects on firms' production processes are considered."[21] Yet even if the Porter hypothesis is only true in a limited number of situations, the potential for innovation to reduce **compliance costs** seems to be generally underestimated. In other words, in many cases firms may incur net costs as a result of environmental regulations, but these costs tend to be much lower than initially expected. Proposed environmental regulations often prompt opposition by industries on the basis of their anticipated compliance costs and negative impacts on the economy.

compliance costs the cost to firms and industries of meeting pollution regulations.

A 1997 study sought instances where compliance costs estimated before an environmental regulation was enacted could be compared with actual compliance costs after the law went into effect.[22] A dozen such cases were found in the United States, including regulations on sulfur dioxide, CFCs, asbestos, and mining. In all cases the original, or *ex ante*, cost estimates were higher than actual, or *ex post,* compliance costs, with the original estimates at least 29 percent higher. In most cases, the ex post compliance costs were less than half the original estimates. The report concluded:

> The case studies reviewed in this report clearly show that environmental regulations that mandate emission reduction at the source generally cost much less than expected. It is not clear to what extent businesses overstate their expected costs for strategic reasons, or to what extent they fail to anticipate process and product technology changes when making early estimates. It is clear, however, that input substitution, innovation, and the flexibility of capital have allowed actual costs to be consistently much lower than early predictions.[23]

A 2000 study based on 28 regulations in the United States found that ex ante initial compliance cost estimates were too high in 14 cases, too low in three cases, and relatively accurate in the remaining cases.[24] The analysis found that the tendency to overestimate compliance costs arises due to "unanticipated use of new technology." Further, those regulations that provide firms with the most flexibility regarding how a regulation is met, particularly those that rely upon economic incentives, tend to result in the "most pleasant surprises on the cost side."[25]

Unfortunately, more recent comprehensive analyses of the accuracy of regulatory cost estimates are not available. A 2014 paper stated that "we are sorely in need of better evidence" and that "it would certainly be useful to high-level decision makers to know how reliable the information they are receiving is—or at least, how reliable it has been in the past."[26] A 2014 study by the U.S. EPA did compare ex ante and ex post compliance costs for five regulations, finding that "several of the case studies are suggestive of overestimation of costs ex ante." However, the authors did not consider their results to be conclusive and that "conducting ex post analysis has proven more challenging than anticipated." They called for better collection of data on compliance costs and further analysis on an expanded set of environmental regulations.

While compliance costs seem to be lower than anticipated, this doesn't mean that these costs are insignificant. For example, a 2014 report sponsored by an organization representing U.S. manufacturers claimed that the cumulative effect of federal regulations was to reduce GDP by about $2 trillion annually, or more than 10 percent of GDP, and that the burden of regulations fall disproportionately on small businesses.[27] The report also noted that the greatest share of the federal regulatory burden was a result of environmental regulations. But the report did not consider the benefits of these regulations, and other studies, which we will discuss in detail in Section 14.4 of this chapter, estimate benefits of environmental regulations that considerably exceed costs. Also, one may question the objectivity of the analysis. For example, cost estimates for many regulations were obtained from a survey of manufacturing companies, who may have a strategic interest in overstating costs.

Decoupling

We have emphasized the ways in which environmental protection and the economy are linked, but it is also worthwhile to think about ways the two can be separated. In many ways, economic growth over time has been associated with an increase in environmental impacts. Consider Figure 14.3, which shows that between 1960 and 1977 global economic growth (measured using GDP) was associated with a similar upward trend in global carbon dioxide emissions. During this period, economic activity increased by a factor of 2.2 while CO_2 emissions increased by a factor of 1.9.

Since 1977, we see in Figure 14.4 that while global economic activity and CO_2 emissions both increased, they were not linked as closely as in Figure 14.3. We can say that the two variables have become somewhat "decoupled" since the late 1970s. Economic activity between 1978 and 2015 increased by a factor of 2.9 while CO_2 emissions increased by only a factor of 1.9.

The term **decoupling** has been defined by the OECD as breaking the link between "environmental bads" and "economic goods."[28] We can differentiate between relative decoupling and absolute decoupling:

- **Relative decoupling**: The growth rate of the environmental bad is positive but less than the economic growth rate. We would say that since the late 1970s carbon emissions and economic growth have become relatively decoupled.
- **Absolute decoupling**: The level of the environmental bad is either stable or decreasing at the same time that the economy is growing. Thus absolute decoupling breaks the linkage between economic growth and environmental degradation.

An example of absolute decoupling is shown in Figure 17.5. In the United Kingdom, real GDP increased by a factor of 2.6 between 1970 and 2013. But during this same period total CO_2 emissions in the country actually decreased by more than 30 percent. Even during the period of rapid economic growth in the 1990s and early 2000s, CO_2 emissions stayed constant or decreased. This was in large part a result of a major shift in energy sources away from coal and toward natural gas, resulting from discoveries of large deposits of relatively inexpensive natural gas in the British North Sea.

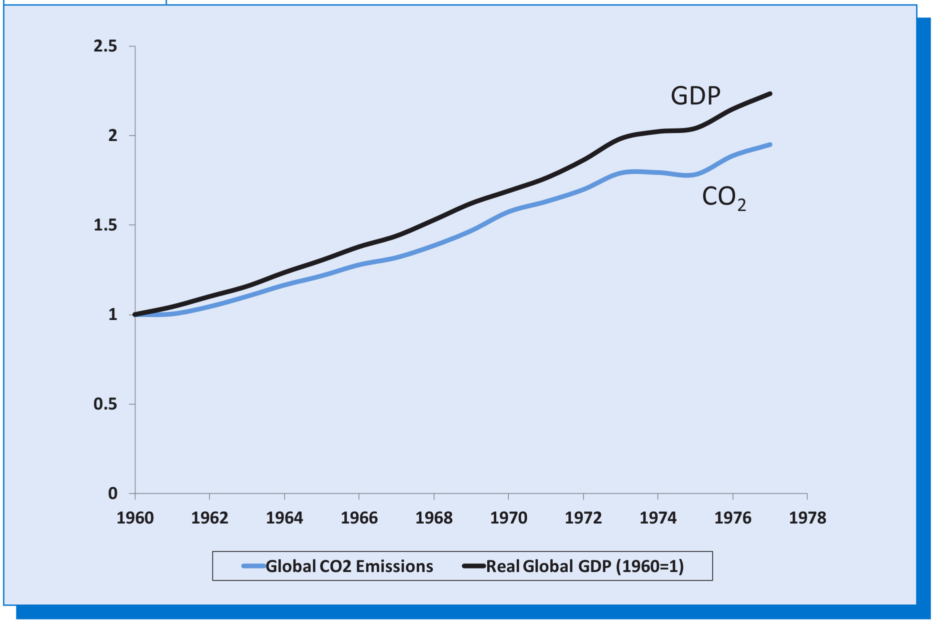
One important proviso is that these CO_2 data don't account for "**exported emissions**"—emissions that are emitted in other countries to produce goods that are exported. Thus some of the decoupling efforts in developed countries have occurred merely because manufacturing has shifted to developing countries. Still, the UK is not alone in absolutely decoupling carbon emissions from economic growth. Over the period 2000–2014 a total of 21 countries reduced their carbon emissions while GDP increased, including Sweden, Germany, France, the United States, and Uzbekistan.[29]

decoupling breaking the correlation between increased economic activity and similar increases in environmental impacts.

relative and absolute decoupling breaking the correlation between increased economic activity and increases in environmental impacts; in absolute decoupling, an increase of economic activity is associated with a decrease in environmental impacts.

exported emissions/pollution shifting the impacts of pollution to other countries by importing goods whose production involves large environmental impacts.

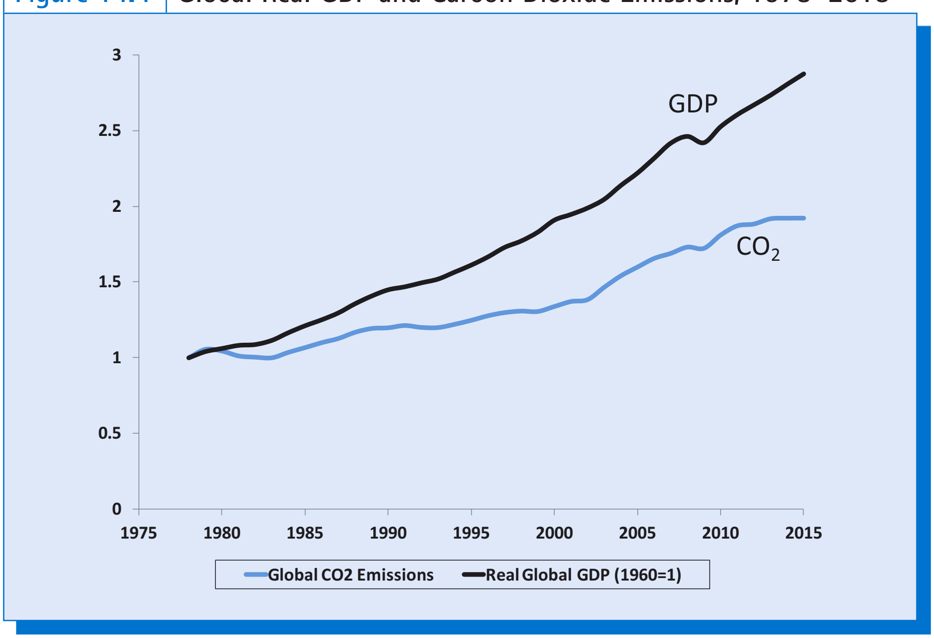
Figure 14.3 Global Real GDP and Carbon Dioxide Emissions, 1960–1977



Source: World Bank, World Development Indicators database.

Note: CO_2 = carbon dioxide; GDP = gross domestic product.

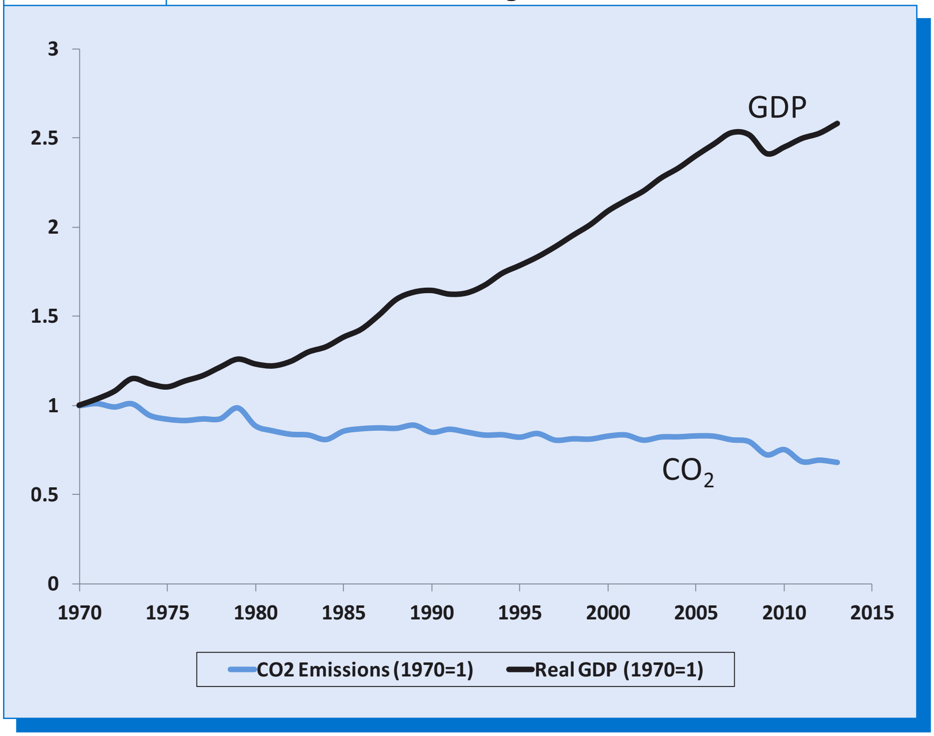
Figure 14.4 Global Real GDP and Carbon Dioxide Emissions, 1978–2015



Sources: World Bank, World Development Indicators database; International Energy Agency, World Energy-related CO_2 Emissions, March 2016.

Note: CO_2 = carbon dioxide; GDP = gross domestic product.

Figure 14.5 Absolute Decoupling: Real GDP and Carbon Dioxide Emissions in the United Kingdom, 1970–2013



Sources: World Bank, World Development Indicators database; U.S. Energy Information Administration, International Energy Statistics.

Note: CO_2 = carbon dioxide; GDP = gross domestic product.

A 2011 report by the United Nations looks at the extent of global decoupling across a range of resources, including fossil fuels, minerals, and wood.[30] The results suggest that a certain amount of relative decoupling has occurred in recent decades "spontaneously," rather than as a direct result of policy intervention. This relative decoupling reflects an increase in the efficiency of production arising from technological improvements. However, some resource extraction rates exceed recent global GDP growth rates. For example, extraction of iron ore, copper, and zinc grew faster than global GDP over the period 1990–2007.[31]

The UN report found that achieving absolute decoupling will require ambitious policies. According to a business-as-usual scenario, global resource use is projected to triple by 2050. Absolute decoupling would keep global resource use constant at or below current levels, which has profound implications for developed and developing countries. In developed countries, resource use would need to decline by a factor of 3–5 to allow enough resource availability for developing countries to improve their living standards. Even then, the more advanced developing nations would still need to reduce their resource use by 10–20 percent in order to permit the poorest countries to somewhat increase their resource use. Thus absolute decoupling at the global level:

> [I]s only conceivable if it is accepted that sustainability-oriented innovations can result in radical technological and system change. Taken as a whole, this would be a scenario

> of tough restraint that would require unprecedented levels of innovation. . . . Most politicians are likely to regard this scenario as too restrictive in terms of developmental goals such as reducing poverty and providing for the material comfort of a rapidly expanding middle class.[32]

More feasible is a scenario of moderate **contraction and convergence**, in which the resource use of developed countries declines (i.e., absolute decoupling), allowing the developing countries to increase their resource use enough to decrease global inequality. According to the UN report, in this scenario global resource use still increases 40 percent by 2050—declining by a factor of two in developed countries but increasing by a factor of about three in developing countries. Even this scenario "would require substantial economic structural change and massive investments in innovations for resource decoupling."[33]

contraction and convergence the concept that overall environmental impacts or economic activity should be reduced at the same time that economic inequalities are reduced.

throughput the total use of energy and materials as both inputs and outputs of a process

Decoupling suggests that economic growth can be possible without an accompanying growth in physical **throughput**. However, current rates of decoupling need to increase in order to avoid a dramatic increase in resource use and pollution over the coming decades. Some nations are already taking the lead with innovative policies to encourage decoupling (see Box 14.2 on Japan's decoupling effort). But major decoupling on a global scale will require a degree of international cooperation not currently evident. In particular, developed countries must be willing to lower their resource use sufficiently to meet sustainability objectives and provide enough resource availability for developing countries to eradicate poverty.

14.3 INDUSTRIAL ECOLOGY

Economic growth has tended to rely on the increased extraction of raw materials and an increase in waste generation. Manufacturing processes have typically been designed to minimize production costs, without consideration of the associated ecological costs. Transitioning to a green economy will require a reassessment of the manufacturing process so that ecological concerns are incorporated into production decisions.

Traditional manufacturing is a "straight-line" process by which raw materials are transformed into final products, generating wastes (including waste heat) that are disposed of into the air, land, or water, as shown in Figure 14.6. These final products are eventually disposed of as they wear out, also becoming waste products.

Natural systems, in contrast to economic systems, typically follow a cyclical pattern, with wastes being recycled and reused. Healthy natural systems show no buildup of pollution and wastes. Inorganic elements such as water and nitrogen cycle through the environment. Dead and decayed organic materials form the basis of fertile soils from which new plant life can grow, in turn supporting new animal life. Rather than creating a problem requiring a solution or disposal, wastes become inputs at a new stage in the cycle.

industrial ecology the application of ecological principles to the management of industrial activity.

The field of **industrial ecology** seeks to model human manufacturing systems on the closed-loop cycles found in nature. The concept of industrial ecology is illustrated in Figure 14.7. Taking this perspective, wastes can potentially become inputs into secondary production. Recycling rates are maximized to reduce the extraction of raw materials. Even waste heat that is typically unutilized can be directed toward productive uses such as heating water or living/working spaces.[34]

Box 14.2
DECOUPLING IN JAPAN

Japan's unique culture norms and geopolitical limits have encouraged creative and effective solutions for decoupling. Japan's high population density and reliance on imports for natural resources have pushed Japan to decouple economic growth from ecological damage. In addition, Japanese culture has a long-standing concept of *mottainai*, meaning essentially that it is a shame when a resource is not utilized to its full potential.

In the 1980s, public concern over pollution from incineration, landfills nearing capacity, and the *mottainai* spirit lead to numerous solid waste reforms, such as replacing old incinerators with state-of-the-art facilities that decoupled dioxin emissions from the voluminous waste incineration. Japan has continued to innovate in solid waste disposal, both on the technical and policy level and has successfully decoupled it from economic growth.

Perhaps Japan's most successful modern decoupling initiative has been the Top Runner Programme (TRP). TRP searches the market for the most efficient product in a category, and makes that the new minimum efficiency standard, with which all companies must comply within four to eight years. As discussed in Chapter 8, standards typically create little incentive for innovation. But the TRP program motivates firms to become the industry efficiency leader, leaving other firms to catch up.

The TRP program has proven remarkably effective. In 10 out of 11 product categories, the efficiency gain was greater than initially expected. For example, diesel freight vehicles were expected to achieve a 6.5 percent efficiency improvement, but instead improved 21.7 percent. Like the Porter hypothesis, the TRP program demonstrates the significant potential for innovation when incentives are well-designed.

Source: UNEP, 2011b.

Recycling rates in the United States and elsewhere have been steadily increasing in recent years, as shown in Figure 14.8. Across the entire U.S. municipal waste spectrum, about 35 percent of total wastes by weight are recycled. Another 12 percent is incinerated to generate heat or electricity. The total amount of waste sent to municipal landfills has actually declined in recent years, from about 175 million tons in 1990 down to 164 million tons in 2012.[35]

Figure 14.6 Straight-Line Process of Traditional Manufacturing

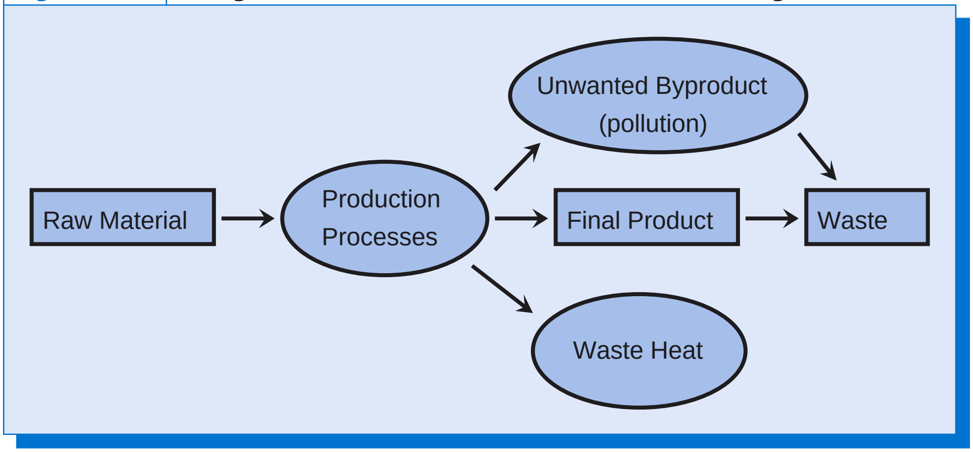


Figure 14.7 Cyclical Production Processes of Industrial Ecology

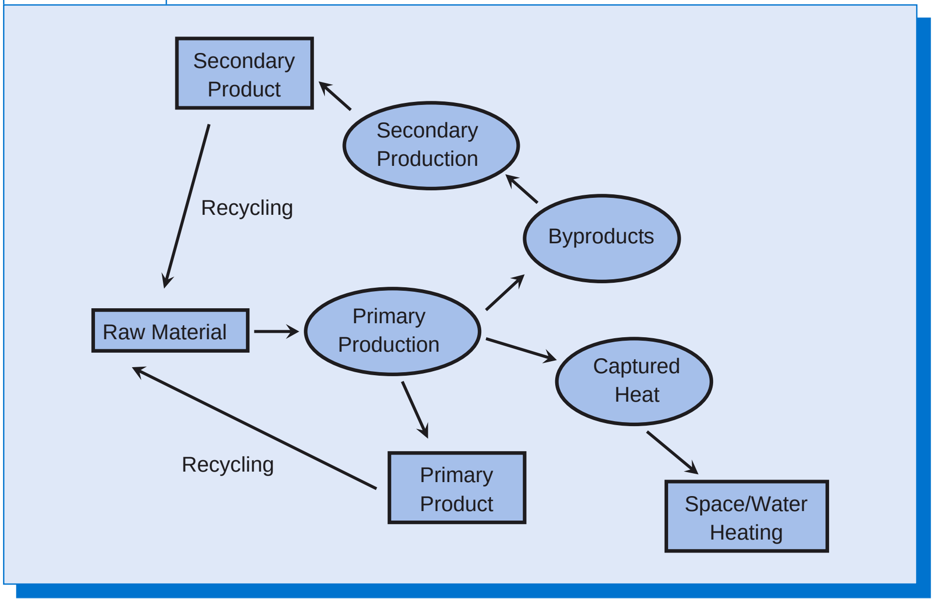
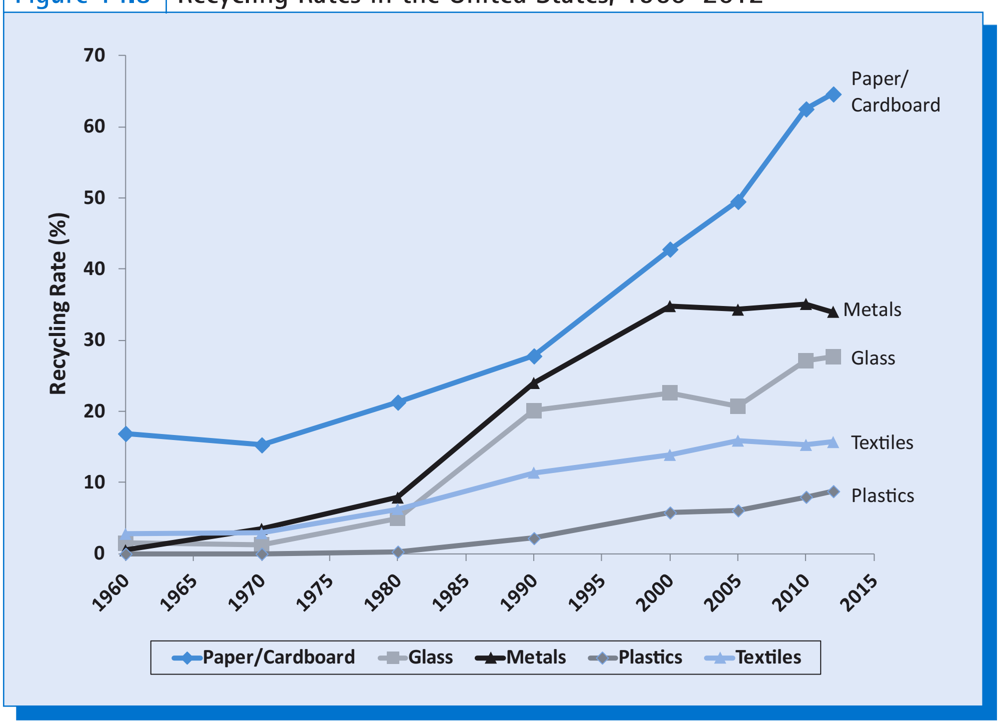


Figure 14.8 Recycling Rates in the United States, 1960–2012



Source: U.S. EPA, 2014b.

The profitability of recycling depends on the demand for recycled products and the relative costs of recycled and virgin materials. One of the reasons that paper recycling rates have increased significantly over the last few decades is that it is generally cheaper to produce many paper products using recycled materials rather than virgin inputs.

A 2007 study of recycling in New Zealand found that the overall recycling rate could be increased from 38 percent to 80 percent while providing society with net economic benefits.[36] The study found that recycling is particularly profitable for paper, used oil, metals, glass, and concrete. The economics of plastic recycling is mixed—while it generally makes economic sense to recycle PET (polyethylene terephthalate; recycling code #1) and HDPE (high density polyethylene; recycling code #2), it is generally not profitable to recycle PVC (polyvinyl chloride; recycling code #3) or LDPE (low density polyethylene; recycling code #4).

In addition to increasing recycling rates, industrial ecology also promotes **dematerialization**—achieving the same economic goal with less materials use. Aluminum beverage cans, for example, contain about 30 percent less metal than they did in the 1970s, and aluminum cans themselves replaced cans made of much heavier metal used in previous decades. Achieving the same function (delivering a beverage to consumers) using less material benefits the supplier, as well as the environment, cutting resource use and transportation costs, and reducing wastes even if the cans aren't recycled.

Another principle of industrial ecology is **materials substitution**—replacing a scarce, hazardous, or highly polluting material with a more environmentally benign substitute. Many uses for copper, for example, have been replaced by plastics, optical fibers, and lighter metals such as aluminum. Government regulation has contributed to the partial replacement of metal-based pigments in paints with organic pigments, reducing the dangers of lead poisoning and the amount of lead and other heavy metals in the waste stream.

> **dematerialization** the process of achieving an economic goal through a decrease in the use of physical materials, such as making aluminum cans with less metal.
>
> **materials substitution** changing the materials used to produce a product, such as using plastic pipe instead of copper in plumbing systems.

14.4 DOES PROTECTING THE ENVIRONMENT HARM THE ECONOMY?

What is the evidence regarding the economic impact of "greening" the economy? Specifically, is there a tradeoff between protecting the environment and the economy and job creation? The conventional wisdom, particularly in the United States, seems to be that such a tradeoff exists:

> Environmental regulation in the United States stands accused of causing a broad array of undesirable economic consequences. The view that environmental regulation seriously harms the U.S. economy is so firmly established that it has become the centerpiece in the series of attempts over the last few years to roll back the very rules that have produced such dramatic improvements in environmental quality.[37]

A 1999 report to the U.S. EPA considered four questions in assessing the impact of environmental protection on the economy:[38]

1. Is environmental protection too expensive?
2. Does protecting the environment result in job losses?

3. Does environmental protection reduce economic growth?
4. Does environmental protection harm international competitiveness?

Let's now consider the empirical evidence to answer each of these questions.

Is Environmental Protection Too Expensive?

The first step to answering this question is to estimate how much is spent on environmental protection. Unfortunately, comprehensive and consistent data on environmental protection spending in the United States are not available. An older, but comprehensive, estimate was produced in a 1990 EPA report which calculated total pollution control expenditures as 2.1 percent of GDP in 1990 (about $100 billion), rising to 2.6–2.8 percent of GDP in 2000.[39] These costs include the cost of complying with environmental regulations, as well as costs that would be incurred in the absence of such regulations, including basic water treatment and trash collection and disposal.

Using a slightly different methodology, the OECD estimated that pollution control expenditures in the U.S. in the mid-1990s were 1.6 percent of GDP.[40] Finally, a 2009 report prepared for the United Nations Environment Programme determined that environmental protection expenditures in the U.S. were $422 billion in 2007, or about 3 percent of GDP.[41] The report also projected that environmental protection expenditures in 2015 would be $439 billion, which equates to 2.4 percent of GDP.

Thus, overall, it seems the U.S. is spending 2–3 percent of its GDP protecting the environment. Is this too much? One answer would consider how environmental protection spending compares with other categories of spending. The 1990 EPA report mentioned above noted that "national environmental pollution control expenditures [are] less than half those for clothing and shoes, one-third those for national defense, one-third those for medical care, one-fifth those for housing, and one-sixth those for food."[42] Thus environmental spending is well within the range of what we spend on other essentials.

Another way to assess U.S. environmental spending is to compare it to spending in other countries. Most European countries report annual environmental protection expenditures using a consistent methodology. While this methodology differs from the approaches used to estimate U.S. expenditures, like the U.S. estimates the European estimates include both public and private expenditures. We see in Table 14.1 that environmental protection expenditures in several European countries range from about 1 percent to 4 percent of GDP. Thus these values suggest that environmental protection expenditures in the U.S., as a percent of GDP, are comparable to the levels found in other industrialized nations.

From the point of view of economic analysis, the most appropriate way to determine whether environmental expenditures are justified is to compare these costs to the benefits society receives. Using the techniques discussed in Chapter 6, one could theoretically estimate the market and non-market benefits of environmental expenditures. However, no comprehensive estimate has been made of the benefits of all environmental regulations in the United States or any other country. Instead, cost-benefit analyses have been conducted for many individual federal regulations. Under various executive orders in the United States, starting with Ronald Reagan and reaffirmed by Barack Obama, federal agencies proposing major regulations must quantify the costs and benefits of the proposal to the extent possible.[43] This requirement applies for non-environmental regulations as well as those related to the environment.

Each year the U.S. Office of Management and Budget publishes a report summarizing the results of cost-benefit analyses for all major regulations enacted that year, and also

Table 14.1 Environmental Protection Expenditures, Selected European Countries, 2012

Country	Environmental Protection Expenditures, as a percent of gross domestic product
Austria	3.3
Estonia	4.1
France	2.2
Hungary	1.7
Lithuania	1.9
Norway	1.7
Poland	2.4
Slovenia	2.3
Spain	1.2
Sweden	1.2

Source: Eurostat database, Environmental protection expenditures.

Note: The percentages are the sum of three separate categories: public sector expenditures, industry expenditures, and public/private specialized producer expenditures. In a few cases data for a particular category and country were not available for 2012. In these cases, the most recent data were used.

the aggregate impact of all regulations over the previous 10 years. Table 14.2 presents the cost-benefit results for various major federal agencies covering the period 2004–2014.[44]

During these 10 years, the U.S. EPA enacted more regulations (30, as well as three in conjunction with the Department of Transportation) than any other federal agency, or about 32 percent of all major federal regulations. The annual costs of these 33 regulations are estimated to be $46–$61 billion. However, the annual benefits are estimated to be $192–$842 billion, implying a benefit-cost ratio of at least 3:1 and as high as 18:1.

While the EPA regulations impose about 60–70 percent of all federal regulatory costs, these regulations generate about three-quarters of the benefits of all regulations. Thus EPA regulations result in slightly higher benefit-cost ratios, on average, than other federal regulations. These results suggest that while environmental expenditures are large, and the EPA does enact more regulations than any other federal agency, environmental regulations provide significant net benefits to society.

Table 14.2 Costs and Benefits of Major Federal Regulations, 2004–2014

Agency	Number of Rules	Annual Benefits (billions)	Annual Costs (billions)
Department of Agriculture	3	1.0–1.4	0.9–1.1
Department of Energy	20	16.4–229.0	6.3–9.0
Department of Health and Human Services	15	17.6–35.7	1.1–4.7
Department of Labor	8	9.0–26.0	2.8–6.2
Department of Transportation	25	18.2–32.4	8.1–16.1
Environmental Protection Agency	30	158.5–782.2	36.9–44.4
Joint DOT and EPA	3	33.0–60.0	8.9–16.9
Total	104	253.7–1166.7	65.0–98.4

Source: U.S. OMB, 2015.

Does Environmental Protection Result in Job Losses?

As mentioned earlier, the purported tradeoff between jobs and the environment is a common critique of environmental regulation. Several research studies have explored the relationship between employment and environmental regulation. While increased environmental spending leads to the loss of certain jobs, it creates other jobs. These effects may cancel out or actually result in a net gain of jobs. For example, a 2008 analysis of the U.S. economy tested the notion that environmental protection results in job losses.[45] Relying on a model of the United States economy, the study was able to estimate how environmental spending and regulation affects employment in various industries. Their major finding was that:

> [C]ontrary to conventional wisdom, [environmental protection (EP)], economic growth, and jobs creation are complementary and compatible: Investments in EP create jobs and displace jobs, but the net effect on employment is positive.[46]

Further, the study found that states that have the strongest environmental regulations also have the best job opportunities. The authors suggested that state-level policies integrate environmental protection as a key component of job creation proposals.

A 2007 study in the United Kingdom also studied the effect of environmental regulation on employment. The results found that regulations had a slightly negative impact on employment, although the results were not statistically significant. They concluded that their analysis found "no evidence of a trade-off between jobs and the environment."[47]

A 2009 review of the literature on the relationship between environmental policies and employment reached the conclusion that strong environmental policies will change the distribution of jobs in society but have little effect on the overall level of employment.[48] Focused on Europe, the study found that well-designed environmental policies can result in net job gains. For example, the additional revenue from higher environmental taxes could be used to reduce the taxes on labor, thus reducing the cost of hiring workers and leading to higher overall employment.

A similar conclusion was reached by a 2016 analysis which estimated the employment impacts of various potential policies to reduce carbon emissions in the United States.[49] For each policy analyzed, the authors' model predicted that job losses in "dirty" sectors, such as coal mining, were essentially offset by job gains in cleaner sectors, such as renewable energy. They concluded that the "overall effects on unemployment should not be a substantial factor in the evaluation of environmental policy" because the net effects are likely to be quite small.[50]

Another 2016 study assessed the relationship between the level of air toxins emitted by over 700 production facilities in the U.S. and the number of "good" jobs at those facilities, defined as jobs in managerial, professional, technical, and craft occupations.[51] This relationship was studied at the national level, as well as by region and industry. In nearly all instances no significant relationship was evident, implying that cleaner facilities provided about the same number of good jobs as dirtier facilities. The authors note that:

> [T]he absence of a clear trade-off between jobs and the environment is striking. There is growing evidence that the cost, in income or jobs, of environmental regulation is often smaller than forecast or that the impact of environmental regulation on employment and economic activity is actually positive. In this study, we find little evidence that more pollution itself is associated with more or better jobs in aggregate, a non-trade-off that should inform policymakers and local public and private decision-makers.[52]

Finally, until 2013 the U.S. Bureau of Labor Statistics (BLS) collected information on the reasons for private-sector mass layoff events in the United States, defined as a company laying off more than 50 workers.[53] One of the potential reasons a firm could have provided for laying off workers was "government regulations," including environmental as well as other regulations. Based on data from 2012 and 2013 involving more than 4,300 layoff events, only 13 events were attributed to government regulations. Thus less than 1 percent of all mass layoffs seem to be a result of any type of government regulation, including environmental regulation.

As several of the above studies indicate, environmental regulations lead to job losses in specific industries, such as coal mining and oil refining, but also create many jobs in other industries. According to one estimate, environmental protection is responsible for about 5 million jobs in the United States.[54] This study found that just like spending in any other sector, environmental spending creates a broad range of jobs:

> [W]e found that classic environmental jobs constitute only a small portion of the jobs created by EP [environmental protection]. The vast majority of the jobs created by EP are standard jobs for accountants, engineers, computer analysts, clerks, factory workers, truck drivers, mechanics, etc. In fact, most of the persons employed in these jobs may not even realize that they owe their livelihood to protecting the environment.[55]

According to a 2012 paper, public investments on clean energy sources in the U.S. create about three times as many jobs as similar spending on fossil fuel energy sources.[56] The reasons are that clean energy sources tend to be more labor intensive, and the money invested is more likely to be spent domestically as opposed to funding imports. Worldwide, renewable energy sources employed over 8 million people in 2015—more than one million each in solar photo voltaics, liquid biofuels, and wind energy.[57] More than half of these jobs are in low- and middle-income countries, mainly China and India.

Does Environmental Protection Reduce Economic Growth?

Another criticism of environmental protection is that it reduces economic growth, based on the results of studies showing that environmental regulations reduce GDP growth rates. For example, a comprehensive analysis of the Clean Air Act in the United States estimated that GNP in 1990 was about 1 percent lower than it would have been without the policy. The aggregate macroeconomic loss from the Act over the period 1973–1990 was estimated to be about $1 trillion. Analysis of the economic impact of major environmental regulations in Europe suggests an aggregate economic loss of about 0.2 percent of GDP.[58]

The aggregate macroeconomic impacts of environmental regulations are normally estimated using **computable general equilibrium** (CGE) models. These models allow economists to determine how impacts in one sector of the economy carry through to employment and income changes in other sectors. The models include feedback loops to model longer-term impacts, particularly how capital investments respond to supply and demand changes in different sectors. However, the results of CGE models must be interpreted with caution.

computable general equilibrium economic models that aim to estimate the effect of policy changes throughout an entire economy.

> CGE models *have to* predict reduced economic growth because of environmental compliance. After all, pollution control costs in these models are treated as extra expenditures necessary to produce the same level of valued output. . . . The outcome

> is implicit in how the model is constructed. So this finding isn't necessarily a complete picture for what people and policymakers want to know about real world regulation, where a pollution control sector emerges as part of the economy, and helps to produce environmental protection, which is also an "output" with value.[59]

CGE models do not estimate the benefits of regulation, particularly those that don't appear in markets. For example, the CGE costs mentioned above regarding the Clean Air Act provide no insight into the benefits of the Act, which can only be obtained with additional economic analysis. When an estimate of the Clean Air Act benefits was made, it was found that the central estimate of the 1973–1990 benefits was $22 trillion, or a benefit/cost ratio of 22:1.[60] CGE models also fail to account for positive feedback loops such as the increase in productivity as negative health impacts decline with better air quality.

So while there appears to be a slight negative impact of environmental regulation on economic growth as traditionally measured, we need a more complete analysis to determine its effect on social welfare. As we saw in Chapter 10, GDP was never intended to measure social welfare, and economists have developed alternative national accounting approaches to supplement or replace GDP. These alternatives may present a better framework for fully assessing the impacts of environmental regulations on social welfare. We need to analyze environmental regulations in light of both their benefits and their costs. The studies reviewed above indicate that environmental regulations provide society with significant net benefits.

Does Environmental Protection Harm International Competitiveness?

Finally, we consider whether environmental regulation makes a nation less competitive than nations with less stringent regulations. Assuming environmental regulations lead to higher production costs, firms having to meet stricter regulations would seem to be at a competitive disadvantage.

Various studies have addressed this issue, commonly looking at how regulations affect the quantity of exports in various sectors of the economy. In general, these studies find that regulations can have negative impacts on certain sectors, particularly those reliant upon fossil fuels, but positive impacts on other sectors. For example, a 2010 paper found that environmental regulations have a positive effect on exports of wood, paper, and textile products, but negative impacts on most other sectors.[61]

A 2011 study of U.S. manufacturing found that highly polluting manufacturing plants tend to be associated with lower overall productivity. The study estimated that inefficiencies associated with the failure to meet Clean Air Act standards lowers productivity by about 5 percent.[62] A 2012 study of European regulations also found evidence that certain regulations can have a positive impact on competitiveness:

> [T]he overall effect of environmental policies does not seem to be harmful for export competitiveness of the manufacturing sector, whereas specific energy tax policies and innovation efforts positively influence export flows dynamics, revealing a Porter-like mechanism. These results show that public policies and private innovation patterns both trigger higher efficiency in the production process through various complementarity mechanisms, thus turning the perception of environmental protection actions as a production cost into a net benefit.[63]

A 2014 paper analyzed the relationship between environmental policy stringency in OECD countries and their rate of productivity growth. The results indicate that increases in the stringency of environmental policies do not harm productivity growth. Instead, tightening environmental policies was associated with short-run increases in productivity. The paper notes that "stringent environmental policies should not be expected to have detrimental effects on productivity, in particular if policies are well-designed" by allowing for easy market entry for new firms with technological leadership.[64]

Finally, another 2014 paper reviewed the literature on the relationship between environmental regulations and productivity and competitiveness and concluded that there is "little evidence to suggest that strengthening environmental regulations deteriorates international competitiveness."[65] The authors note that the benefits of environmental regulations usually vastly outweigh the costs, and that well-designed policies can spur innovation and promote economic growth as a society transitions from "dirty" to "clean" technologies.

What Conclusions Can We Draw?

The evidence suggests that the common notion that environmental regulation harms the economy is a myth. While regulations may harm particular industries, mainly those relying upon fossil fuels, the benefits of environmental regulations consistently outweigh the costs. Further, well-designed regulations can actually have a net positive impact on economic growth and competitiveness, and foster job creation.

14.5 CREATING A GREEN ECONOMY

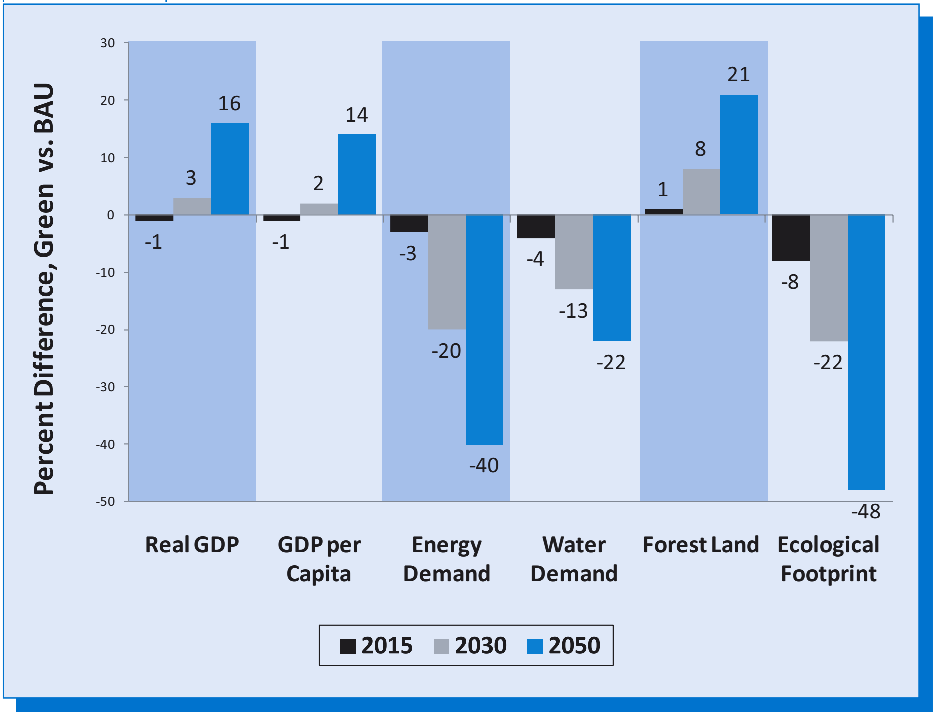
The transition to greener economies has already started, driven by economics and government policies. For example, as we saw in Chapter 11, the world is now adding more renewable energy capacity each year than fossil fuel capacity.[66] However, rates of decoupling, recycling, and dematerialization are generally not occurring fast enough to achieve sustainability targets such as reducing CO_2 emissions or protecting biodiversity. The United Nations concludes that "we are very far from being a green economy."[67]

Creating a green economy will require a significant shift in investments in infrastructure, research, and development. UNEP has developed a complex model to analyze the economic and environmental impacts of directing investments to promote a transition to a green economy.[68] They consider a green scenario where 2 percent of global GDP is invested in various ways to promote sustainability, including energy efficiency, renewable energy, waste management, infrastructure improvements, agricultural production methods, and water management. They compare the results of this green economy scenario to a business-as-usual scenario where investment rates follow existing trends.

The results are shown in Figure 14.9, indicating the percentage difference in various variables for the green economy scenario relative to the BAU scenario. In the short-term (2015), the green economy scenario results in about 1 percent lower real GDP and lower GDP per capita. But in the longer term the green economy shows substantially better economic performance than the BAU scenario. By 2050 real GDP in the green economy scenario is 16 percent higher than in the BAU scenario. The environmental differences between the two scenarios are initially small, but become dramatic over the following decades. By 2050 global energy demand is 40 percent lower in green economy scenario, and the ecological footprint is 48 percent lower.

Green investments are also relatively job-intensive, particularly in the agricultural, forestry, and transport sectors. In the energy sector, employment would initially decline as jobs related to fossil fuel use decline, but in the long run (after about 2030) net employment rises, primarily as a result of the creation of millions of jobs related to energy efficiency.

Figure 14.9 Environmental and Economic Projections, Green Economy Scenario versus Business-As-Usual



Source: UNEP, 2011a.

Note: BAU = business-as-usual; GDP = gross domestic product.

The UNEP model finds that investments for the green economy particularly benefit the world's poorest. The poor disproportionately depend upon natural resources for their livelihood. So investments in natural capital, including water resources, sustainable agriculture, and forests increase incomes while also improving the environment. Investments in natural capital also foster ecotourism, which offers another way to increase incomes in developing countries. In the energy sector, investment in renewable energy can also benefit the world's poor. There are about 1.6 billion people in the world who lack access to electricity. Given the lack of an existing distribution grid in many poor regions, small-scale off-grid solar energy is currently more cost-effective than electricity generated using traditional fossil fuels.

The transition to a green economy will require more than investment; it will involve major policy shifts at the national and international levels. The policy recommendations from the UNEP report include:

- *Use taxes and other market-based instruments to internalize negative externalities.* As we've seen in other instances in the book, pricing pollution promotes more efficient resource use and encourages innovation. Well-designed taxes or permit systems can also be net job creators. For example, a German tax on fossil fuels and electricity, introduced in 1999 and slowly phased in over several years, used the revenues to reduce the costs of hiring employees by lowering firms' required social security contributions. The tax was estimated to have created 250,000 full-time equivalent jobs while also reducing carbon emissions.

- *Decrease government spending that depletes natural capital.* We discussed the distortionary impact of fossil fuel subsidies in Chapter 11. Similarly, inefficient fishery subsidies can lead to over-exploitation of fisheries, to be discussed in Chapter 18. Subsidy reforms should be phased in slowly to reduce negative economic impacts, and be supplemented with policies to protect the poor. In Indonesia, for example, reductions in energy subsidies in 2005 and 2008 were implemented along with cash transfers to low-income households.

- *Efficiency and technology standards can sometimes be more cost-effective and easier to administer than market-based instruments.* Developing countries often lack the institutions for complex tax and tradable permits systems. Technology standards are easier to enforce, and can ensure a rapid transition to the best available technologies. The challenge is to set appropriate standards, and adjust them as new technologies become available. Standards for government procurement have been demonstrated to be an effective way to jump-start the demand for environmentally friendly goods and services.

- *Temporary support measures are needed to ensure an employment transition for affected workers.* As shown in Figure 14.9, in the short term the transition to a green economy will cause a slight decline in GDP. Training will be needed to provide displaced workers with the skills to gain new jobs in the green economy. In many cases workers will remain employed in their current jobs, but through skill enhancement they can learn to do their jobs in new ways. Construction workers will still build houses, but construction techniques can incorporate better insulation, solar photovoltaic systems, and more efficient lighting.

- *International environmental governance needs to be strengthened.* Even with the potential economic benefits of green economy policies, individual nations remain hesitant to act alone. Strong international agreements create a level playing field and are the only effective way to deal with global environmental issues such as climate change and ozone depletion. An important step toward a green economy would be to reform international trade laws, as we'll discuss further in Chapter 21. For example, international trade agreements can be set to reduce harmful subsidies while lowering certain tariffs to foster trade in environmental goods and services. Current trade laws on intellectual property rights have been criticized for failing to meet the needs of developing countries, and actually inhibiting the development of green markets. In some cases developing countries will need greater flexibility in protecting infant industries. Finally, developing countries often have an advantage in markets for ecosystem services such as carbon sequestration and watershed protection. International agreements that create markets for these services can reduce poverty while enhancing natural capital.

While some of these recommended policies will require major changes in current political institutions, others, such as reducing harmful subsidies or increasing efficiency standards, can be relatively easily and quickly implemented. The transition to a green economy will be a major issue confronting all economic policy makers in the coming decades. Significant steps are already being taken, as a greater share of public investment is directed toward greening the economy. Global investment in clean energy, including energy efficiency, increased by more than a factor of four between 2004 and 2011, as shown in Figure 14.10.

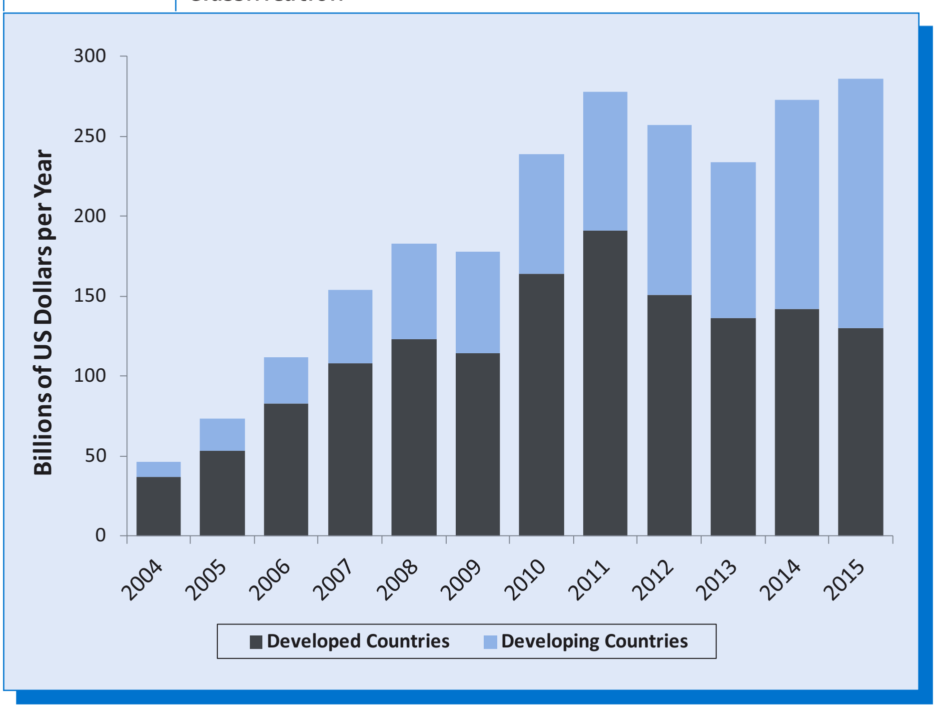
The increase between 2009 and 2011 was driven by stimulus programs in response to the 2007 global financial crisis. According to the World Bank, about 16 percent of the global stimulus spending enacted as a response to the crisis was classified as "green" stimulus—spending on renewable energy, energy efficiency, waste management, and water sustainability.[69] The leader was China, spending $221 billion on green stimulus, about half of it directed toward rail transport. The United States allocated $112 billion as green stimulus, with about $30 billion each invested in renewable energy and energy efficient buildings. The European Union allocated about 60 percent of its stimulus spending toward green measures, including carbon capture and storage and electricity grid efficiency.

As stimulus spending was reduced or eliminated in various countries, clean energy investments also declined in 2012 and 2013. But in 2014 and 2015 global green investments began to increase again, setting a new record in 2015. An important result in Figure 14.10 is the significant increase in clean energy investments in developing countries. In the mid-2000s only about one-quarter of global clean energy investments took place in developing countries. But while green energy investments in developed countries increase by a factor of 3.5 over 2004–2015, investments in developing countries increased by a factor of 17 during this period! In fact, 2015 marked the first year in which clean energy investments in developing countries exceeded those in developed countries.

This is particularly significant because, as we saw in Chapter 11, most of the projected increase in global energy demand will occur in developing countries. If developing countries can rely primarily upon renewable energy sources to meet this growing demand, then meeting climate and other environmental goals becomes much more feasible.

Countries that have been the "first movers" toward a green economy are already starting to realize the benefits. South Korea has pledged 2 percent of its GDP toward investment in green sectors. Recent efforts there to increase recycling rates have saved billions of dollars and created thousands of jobs.[70] Since the 1990s Germany has been pursuing green growth mainly through pricing negative externalities, removing inefficient subsidies, and supporting clean technology investments. According to the OECD, Germany has one of the world's highest levels of resource productivity, with an internationally competitive environmental

Figure 14.10 Global Clean Energy Investments, 2004–2015, by Country Classification



Source: UNEP and Bloomberg New Energy Finance, 2016, Figure 4.

goods and services sector.[71] Employment in the renewable energy sector tripled between 2002 and 2010. Germany was also one of the most resilient developed nations after the global financial crisis. China's eleventh five-year plan, covering 2006–2010, allocated significant investments toward renewable energy and energy efficiency. According to UNEP, China's clean energy investments are creating hundreds of thousands of job per year and have led to major advances in the development of wind and solar power technologies.[72]

Despite the growing evidence of the environmental and economic effectiveness of clean energy investments, much more still needs to be done. According to the United Nations, current clean energy investments are only about 30–40 percent of the necessary levels to achieve climate goals.[73] In addition to increasing investments, the UN calls for industrial policies to foster renewable energy, transitional policies to help displaced workers from the fossil fuel sector, and a focus on reducing poverty in developing countries.

Responding to climate change, biodiversity losses, and other environmental issues are some of the most profound challenges humans face in the twenty-first century. This chapter demonstrates that we can meet these challenges without sacrificing economic performance. Building on recent successes, the key is to maintain and extend these efforts through bold initiatives, long-term thinking, and international cooperation.

Summary

The concept of a "green economy" is that improved human well-being and reduced inequality can be driven by investments to reduce environmental impacts. It is based on the finding that economic growth is compatible with protecting the environment.

The relationship between the economy and the environment can be analyzed based on several theories. The environmental Kuznets curve (EKC) hypothesis is that economic growth eventually leads to a reduction in environmental impacts. The empirical evidence supports the EKC hypothesis for some pollutants, but it does not apply to other environmental impacts, most importantly to carbon emissions. The Porter hypothesis states that well-designed environmental regulations can actually result in lower costs for firms. Again, the theory is valid in some cases but the evidence finds it does not apply to all regulations. The concept of decoupling suggests that economic growth can be "delinked" from negative environmental impacts. Absolute decoupling has occurred in some instances, particularly the decoupling of carbon emissions from economic growth in some developed countries, but greater decoupling progress is needed to achieve sustainability targets.

The field of industrial ecology seeks to maximize resource efficiency and recycling. It promotes using the wastes from one industry as the inputs into additional production. Through dematerialization products can be constructed using a smaller volume of materials. Another focus of industrial ecology is to use materials that are nontoxic, recyclable, and low-polluting.

The common perception that protecting the environment harms the economy is not borne out by numerous studies. The evidence indicates that the benefits of environmental regulations far exceed their costs. Rather than leading to job losses, protecting the environment through well-designed policies can actually be a source of net job creation. Environmental protection does not harm international competitiveness and has little effect on GDP growth rates.

While creating a green economy will entail short-term costs, the long-term benefits are projected to be significant. Rates of GDP growth are expected to be higher under a green economy scenario than a business-as-usual scenario, while environmental impacts are significantly reduced. The transition to a green economy will require strong policy action, including increasing investment, eliminating harmful subsidies, training workers, using economic policy instruments such as taxes and tradable permits, and international agreements that protect the environment.

Key Terms and Concepts

compliance costs

computable general equilibrium

contraction and convergence

decoupling

dematerialization

exported emissions

environmental Kuznets curve (EKC)

green economy

industrial ecology

luxury good

materials substitution

normal good

Porter hypothesis

relative and absolute decoupling

throughput

Discussion Questions

1. What news stories have you heard recently that refer to the interaction between the environment and the economy? Was environmental protection presented as compatible with economic growth? What were the various points of view presented in the story? What is your opinion of the story?
2. What steps, if any, do you think should be taken to promote a green economy in your country or region? What steps do you think would be most effective? Can you propose policies that businesses may support?
3. What groups would be hurt most by the transition to a green economy? What groups would most benefit from the transition? Can you think of scenarios in which those who gain could compensate those who would be hurt?

Notes

1. UNEP, 2011a, p. 16.
2. UNEP, 2011a, *Synthesis for Policymakers*, pp. 1–2.
3. Yandle *et al.*, 2004.
4. Beckerman, 1992, p. 482.
5. The EKC hypothesis is named after Simon Kuznets, an economist who proposed a similar relationship between income inequality and economic growth in the 1950s.
6. Liddle and Messinis, 2015.
7. The trendline is a second-degree polynomial, which attempts to fit a U-shaped or inverted-U pattern.
8. Aslanidis, 2009.
9. Georgiev and Mihaylov, 2015.
10. Ichinose *et al.*, 2015.

11. Georgiev and Mihaylov, 2015.
12. Akpan and Abang, 2014, p. 16.
13. Porter and van der Linde, 1995.
14. Ibid., p. 98.
15. Murty and Kumar, 2003.
16. Rassier and Earnhart, 2015.
17. Broberg *et al.*, 2013.
18. Lanoie *et al.*, 2011.
19. Quiroga *et al.*, 2007.
20. Koźluk and Zipperer, 2014, p. 174.
21. Rexhäuser and Rammer, 2014, p. 164.
22. Hodges, 1997.
23. Ibid., p. 12.
24. Harrington *et al.*, 2000.
25. Ibid., p. 314.
26. Simpson, 2014, p. 330 and 331.
27. Crain and Crain, 2014.
28. OECD, 2002.
29. Aden, 2016.
30. UNEP, 2011b.
31. Jackson, 2009.
32. UNEP, 2011b, pp. 30 and 32.
33. Ibid., p. 31.
34. See Ayres and Ayres, 1996 and Socolow *et al.*, 1994, for an overview of industrial ecology, and Cleveland and Ruth, 1999, on materials flows in the industrial process.
35. U.S. EPA, 2014a.
36. Denne *et al.*, 2007.
37. Arnold, 1999, Summary.
38. Ibid.
39. Carlin, 1990.
40. OECD, 2007.
41. MIS, 2009.
42. Carlin, 1990, p. vii.
43. A major regulation is generally defined as one that has an impact on the economy of at least $100 million annually.
44. U.S. Office of Management and Budget, 2015.
45. Bezdek *et al.*, 2008.
46. Ibid., p. 63.
47. Cole and Elliott, 2007, p. 1.
48. Rayment *et al.*, 2009.
49. Hafstead and Williams, 2016.
50. Ibid., p. 30.
51. Ash and Boyce, 2016.
52. Ibid., p. 30.
53. See http://www.bls.gov/mls/.
54. Bezdek *et al.*, 2008.
55. Ibid., p. 69.
56. Pollin, 2012.
57. IRENA, 2016.
58. Commission of the European Communities, 2004.

59. Arnold, 1999, p. 10.
60. Commission of the European Communities, 2004.
61. Babool and Reed. 2010.
62. Greenstone *et al.*, 2011.
63. Constantini and Mazzanti, 2012, p. 132.
64. Albrizio *et al.*, 2014.
65. Dechezleprêtre and Sato, 2014, p. 3.
66. Randall, 2015.
67. UNEP, 2011a, *Synthesis for Policymakers,* p. 3.
68. UNEP, 2011a.
69. Strand and Toman, 2010.
70. http://www.unep.org/greeneconomy/AdvisoryServices/Korea/tabid/56272/Default.aspx.
71. OECD, 2012.
72. http://web.unep.org/greeneconomy/success-stories-5.
73. UNIDO and Global Green Growth Institute, 2015.

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Web Sites

1. **http://web.unep.org/greeneconomy/.** The United Nations' page on the Green Economy, including their Green Economy report, national case studies, and several videos.
2. **http://is4ie.org/.** Homepage for the International Society for Industrial Ecology, with links to their journal, job postings, and events.
3. **www.epa.gov/learn-issues/learn-about-greener-living.** The U.S. EPA's site on green living, including numerous tips on how to reduce your environmental impacts.
4. **www.thegreeneconomy.com/.** Homepage for "The Green Economy" magazine, with articles and news stories targeted toward businesses leaders seeking to take advantage of green opportunities.
5. **www.theguardian.com/environment/green-economy.** Web page assembled by *The Guardian*, a UK newspaper, which collects stories related to the green economy.

PART

V

Population, Agriculture, and Resources

CHAPTER 15

Population and the Environment

Contributing author Anne-Marie Codur

Chapter 15 Focus Questions

- How fast is world population growing?
- What are the prospects for future population growth?
- What relationship exists between population and economic development?
- How does population growth affect the global environment and climate change?
- What population policies are effective?

15.1 THE DYNAMICS OF POPULATION GROWTH

Human population has grown slowly throughout most of our history. Only within the past 200 years has rapid global population growth become a reality. Figure 15.1 shows the history of global population increase during the nineteenth and twentieth centuries, together with a United Nations "medium-variant" projection for the twenty-first century.[1] As the figure shows, in the past 100 years, population growth has accelerated at a pace unprecedented in global history. The rate of growth is now slowing, but as the projections show, considerable further increase is expected before population stabilization. As we will see, there can be significant variation in population projections, but it is virtually certain that global population will continue to grow for decades.

In 1800, global population stood at about 1 billion after many centuries of slow growth. By 1950, the total had reached 2.5 billion. Rapid acceleration in growth rates after World War II doubled world population to 5 billion in less than 40 years (by 1987). By 2000, world population had passed 6 billion, and by the end of 2011 it reached 7 billion. In 2015 the population was 7.349 billion. Extraordinarily rapid population growth—about 2 percent per year—occurred from 1960 to 1975. At first glance, 2 percent may not sound so remarkable, but at this rate of growth, population doubles in about 35 years.[2] After 1975, the growth rate slowed, but the much larger size of total population meant that the absolute number of people added each year has not yet declined significantly (see Figure 15.2).

During this period of extremely rapid growth, various authors sounded the alarm regarding the dangers of **exponential growth**. A population of 5 billion that continued to grow at 2 percent per year, for example, would reach 20 billion in 70 years and 40 billion in a little over a century. Finding food, water, and living space for such a vastly increased population would be impossible.

Authors such as Paul and Anne Ehrlich have repeatedly warned since the late 1960s that humanity was on a collision course with the natural world and that runaway population growth could overcome all the benefits of modern science and economic growth, leaving a devastated and miserable planet—revisiting the nineteenth-century predictions of Thomas Malthus, discussed in Chapter 2, that population growth would outrun food supplies.[3] This **neo-Malthusian perspective** has gained much attention and provides the starting point for the modern debate on population growth.

Those who find the Ehrlichs' perspective overly negative often point out that **population growth rates** have been declining since the 1970s; as of 2015, the overall global rate had fallen to 1.18 percent and is expected to continuing falling (Figure 15.3). Does this mean that population will soon stabilize, and fears of rapid growth are mere alarmism? Unfortunately not.

According to UN figures, the global **gross annual population increase** as of 2015 was 83 million. This annual addition to the planet's human inhabitants is the equivalent of more than the entire population of Germany. Every year, the population increases by more people than during the 1960s, when the rate of growth (expressed in percentage terms) was highest (see Table 15.1 and Figures 15.2 and 15.3). The equivalent of a new Hong Kong every month, a new France every nine months, a new India in about 15 years—this is hardly cause for complacency.

exponential growth a value that increases by the same percentage in each time period, such as a population increasing by the same percentage every year.

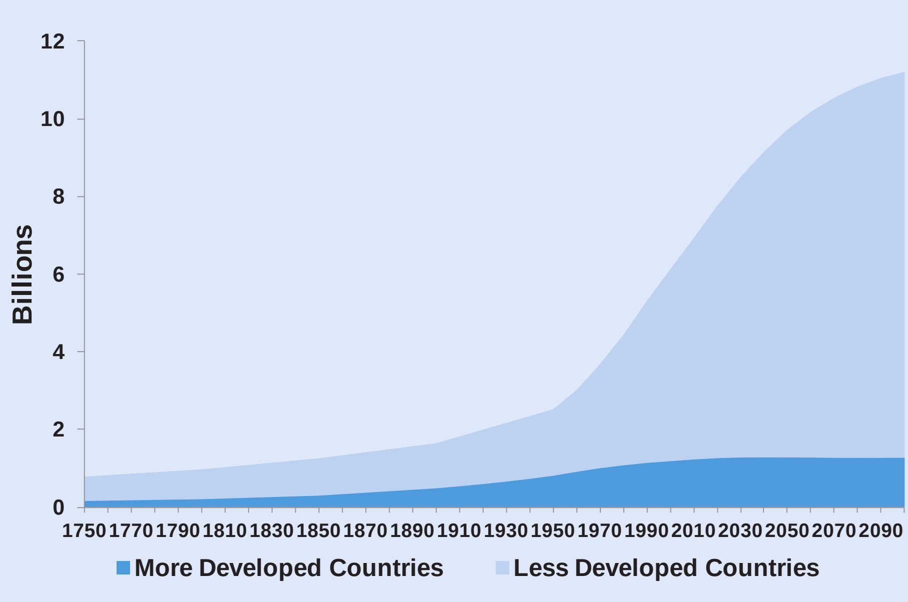
neo-Malthusian perspective the modern version of Thomas Malthus's argument that human population growth can lead to catastrophic ecological consequences and an increase in the human death rate.

population growth rate the annual change in the population of a given area, expressed as a percentage.

gross annual population increase the total numerical increase in population for a given region over one year.

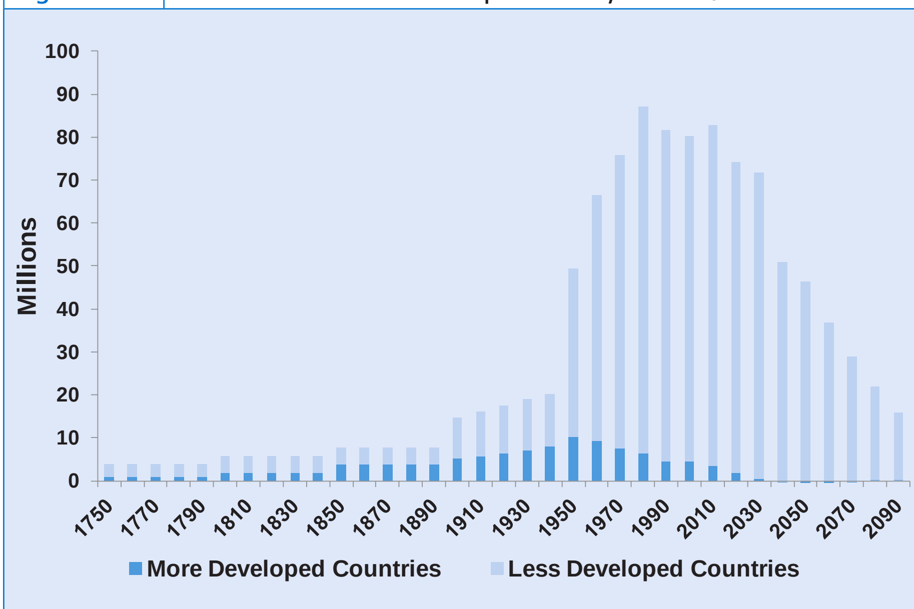
Current medium-variant projections presented in the 2015 United Nations Population Report show population reaching 10 billion just before 2060, then growing at a slower pace to reach 11.2 billion at the end of the century, and eventually peaking in the early part of the

Figure 15.1 Global Population Growth and Projections, 1750–2100



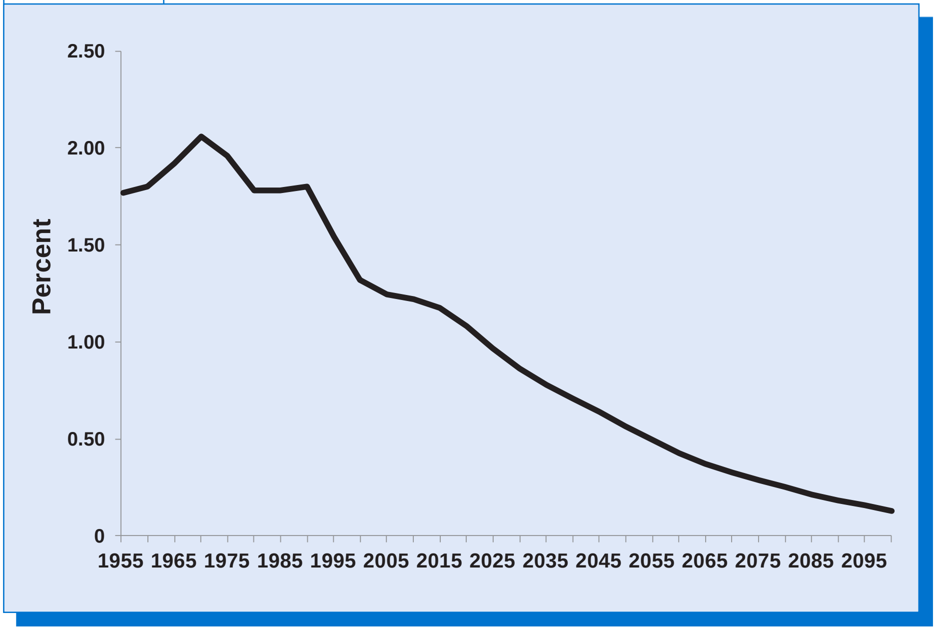
Sources: Caldwell and Schindlmayr, 2002; United Nations, 2015.

Figure 15.2 Net Annual Increase in Population by Decade, 1750–2100



Sources: Repetto, 1991; United Nations, 2015.

Figure 15.3 World Population Growth Rate, 1950–2010, with Projections to 2100



Source: United Nations, 2015.

twenty-second century somewhere close to 12 billion.[4] This represents a significant increase over the 2010 United Nations medium scenario, which showed world population peaking at 10 billion by 2100. The discrepancy between the projections in 2010 and in 2015 arises from the fact that population growth rates have not dropped as fast as expected, especially in Africa. But note that the medium-variant scenario presented by the UN can be characterized as a kind of "business-as-usual" baseline, which rests on the assumption that no rapid reduction in population growth rates will occur in the near future. Other possible scenarios have been suggested, with a more rapid decline in growth rates and earlier stabilization—we will examine this possibility in more detail later.

A very important aspect of population growth is its regional pattern. Population growth will be most rapid precisely in the poorest and most hard-pressed countries. More than 90 percent of the projected growth will come in currently developing countries in Asia, Africa, and Latin America, with especially rapid growth in Africa (see Table 15.2).

Figure 15.4 presents the population distribution among the six major geographic areas. In 2015, Asia represented 60 percent of the world's population, and Africa accounted for 16 percent. According to the medium projection of the UN, this picture will be quite different at the end of the century, with Asia's share decreasing to 43 percent, while Africa's share will

Table 15.1 Global Population Growth Rates and Average Gross Annual Increase

	1950s	1960s	1970s	1980s	1990s	2000s	2010s
Population growth rate (%)	1.80	2.00	1.90	1.80	1.40	1.23	1.18
Average annual increase (millions)	50.6	65.7	75.6	85.3	81.6	76.5	83.8

Source: United Nations, Department of Economic and Social Affairs, Population Division (2015). *World Population Prospects: The 2015 Revision.* New York: United Nations.

Table 15.2 Population of the World and Major Areas, 2015, 2030, 2050, and 2100, Medium-Variant Projection

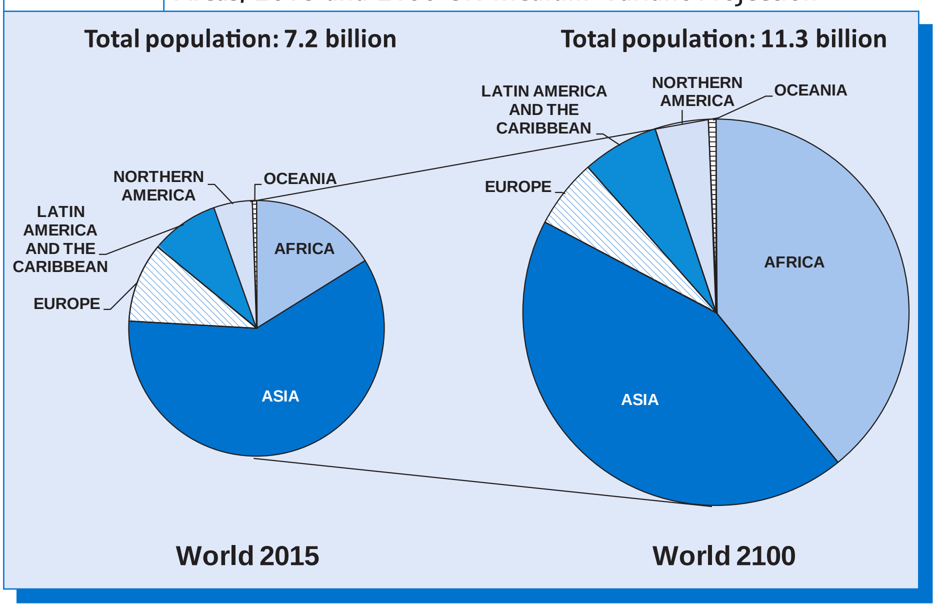
Major Area	*Population (millions)*			
	2015	*2030*	*2050*	*2100*
World	7349	8501	9725	11213
Africa	1186	1679	2478	4387
Asia	4393	4923	5267	4889
Europe	738	734	707	646
Latin America and the Caribbean	634	721	784	721
Northern America	358	396	433	500
Oceania	39	47	57	71

Source: United Nations, Department of Economic and Social Affairs, Population Division (2015). *World Population Prospects: The 2015 Revision*. New York: United Nations.

rise to 39 percent. Meanwhile the share of Europe (including Russia) will decrease from 10 percent to 5.7 percent.

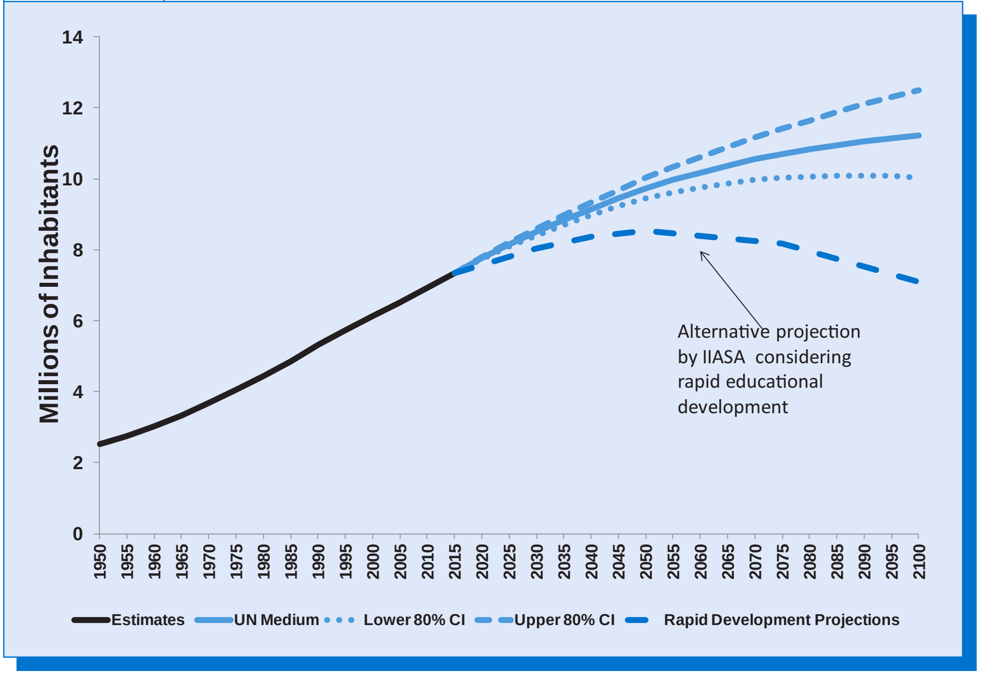
Many of the countries that are experiencing the fastest demographic growth, especially in Sub-Saharan Africa, already have trouble providing adequate food supplies and basic goods to their present population. The population growth that these countries are poised to face in the next decade will undoubtedly put even more pressures on already scarce resources. For this reason, population and its future are of fundamental importance to any discussion of global environmental issues.

Figure 15.4 Distribution of the World Population in Six Major Geographic Areas, 2015 and 2100 UN Medium-Variant Projection



Source: United Nations, 2015.

Figure 15.5 United Nations Estimates for Future Population. Medium-Variant Projection and 80 Percent Confidence Intervals, 2015–2100, and Alternative "Rapid Development" IIASA Scenario



Sources: United Nations, 2015; Lutz *et al.*, 2014.

15.2 PREDICTING FUTURE POPULATION GROWTH

How well can we predict future population growth? The projected population shown in Figure 15.1 is a baseline medium-variant projection. Could the actual figures be much higher or much lower? As Figure 15.5 shows, assumptions about changes in birthrates significantly influence projections. Projections made by the Population Division of the United Nations take into account various hypotheses. The medium-variant projection assumes a steady decline of fertility for countries where large families are still prevalent, as well as a slight increase of fertility in several countries with fewer than two children per woman on average. The projection methodology allows for estimating confidence intervals around the medium-variant trajectory. The area of possible futures, within an 80 percent interval of confidence, is shown in Figure 15.5, indicating that the global population will be somewhere between 8.4 and 8.6 billion in 2030 and between 10 and 12.4 billion in 2100.

Alternative projection scenarios have been proposed based on the implementation of specific policies aimed at speeding up the decline of fertility. A 2014 study presents a scenario with a rapid decrease in fertility, and a stabilization of the world population in the second part of the century, based on extensive investment in education and family planning. In this scenario, world population peaks at around 9 billion and then declines to 8.5 billion at the end of the century.[5] This alternative scenario is shown in Figure 15.5.

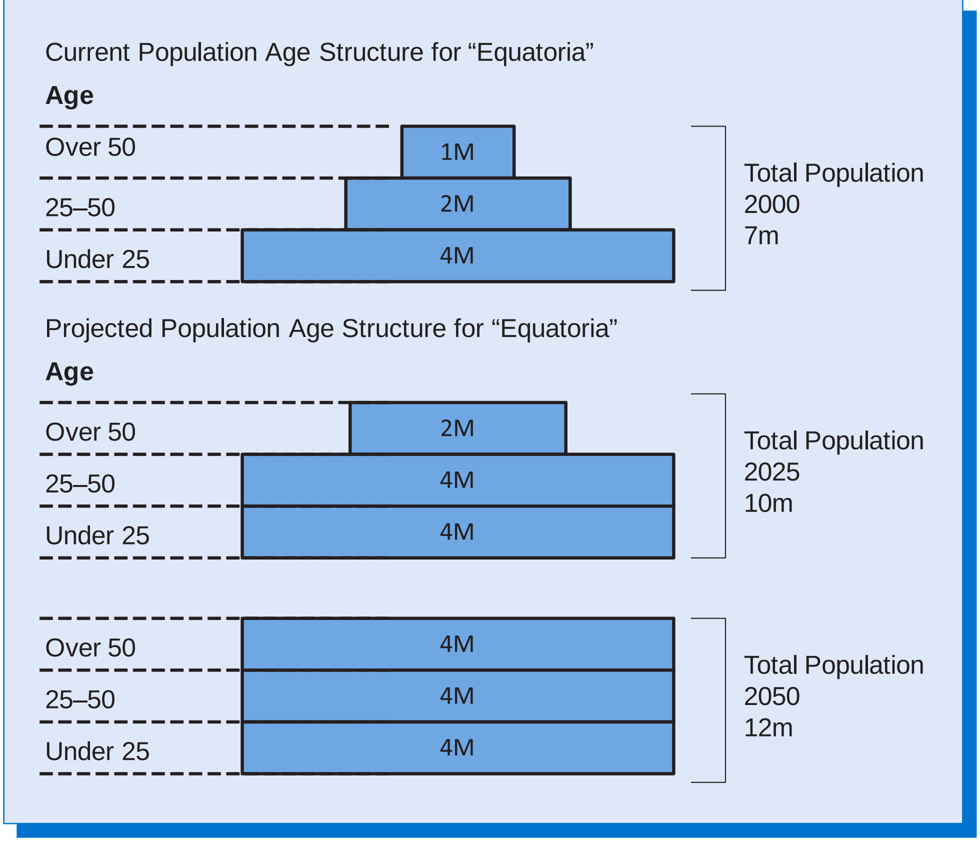
population momentum the tendency for a population to continue to grow, even if the fertility rate falls to the replacement level, as long as a high proportion of the population is in young age cohorts.

population age profile an estimate of the number of people within given age groups in a country at a point in time.

Within the broad range of possible demographic futures, the major factor lending credibility to projections of continued population growth is the phenomenon of **population momentum**. To understand population momentum, let's consider a hypothetical country, Equatoria, which has been experiencing rapid population growth for several generations. For the sake of simplicity, we define a generation as equal to 25 years and divide the population of Equatoria into three age categories: under 25, 25–50, and more than 50 years old. The population age structure in Equatoria depends on the birthrate in previous generations. Suppose that, up to the present, each generation has been roughly twice as large as the preceding generation. This will create a **population age profile** shaped like a pyramid (Figure 15.6). With this age structure, the total population will double every 25 years, since each new generation is twice as large as its parents' generation. The overall population growth rate of the country will average about 3 percent per annum.[6]

This is a high but not unprecedented rate in developing countries—the current population growth rates in Uganda, Tanzania, South Sudan, Niger, Senegal, Gambia, and Mali, for example, are 3 percent or more.

Figure 15.6 Projected Population Age Structure for "Equatoria"



Now consider the future demographics of Equatoria. If this growth rate continues, with the population doubling every 25 years, there will be a situation of exponential growth. If the population was 7 million in 2000, as shown in our diagram, it will be 14 million by 2025, 28 million by 2050, and 56 million by 2075. No country can long withstand the environmental and social pressures of such growth. But, of course, the growth rate may decline.

For this to happen, the average **fertility rate** must fall. The fertility rate is defined as the number of children borne by the average woman during her lifetime. The fertility rate in Equatoria must be around 5 children per woman to account for such rapid rates of growth. Again, this is not unusual in developing countries. The average fertility rates in sub-Saharan Africa during the period 2010–2015 were often higher than 5 children per woman: 5.7 in Nigeria, 6.4 in Mali, and 7.6 in Niger. In other parts of the world, high levels of fertility can be found in countries such as Guatemala (3.3 children per woman), Iraq (4.6), and Afghanistan (5.1).[7]

fertility rate the average number of live births per woman in a society.

replacement fertility level the fertility level that would result in a stable population.

Stabilizing population requires achieving a **replacement fertility level**, which is just over 2 children per woman (the precise number depends on the rate of infant and child mortality). At replacement fertility level, each new generation will be exactly the size of the preceding one. Lowering the fertility rate usually takes many years in a country such as Equatoria. Suppose that Equatoria reaches this goal. Does this mean that the population growth problem is over? Absolutely not!

Imagine a fantastically effective population policy that lowers fertility to replacement level *immediately*. Equatoria's demographic future would then be as shown in the second and third parts of Figure 15.6. Each new generation would be exactly the size of the last. The current generation of under-25s, however, is Equatoria's largest ever. Even at replacement-level fertility rates, the population will continue to grow for two more generations.

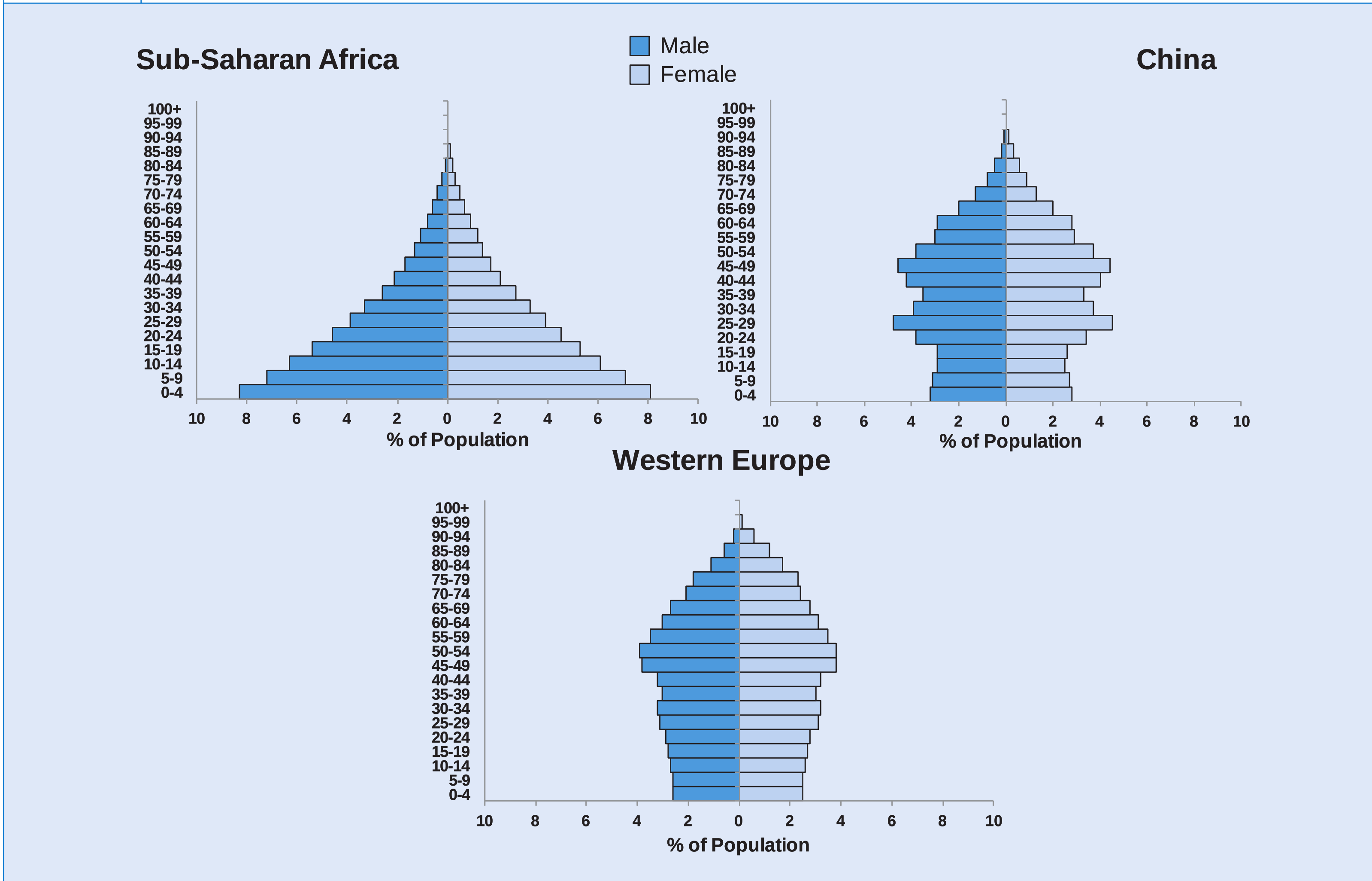
The next generation of children will be four times as large as the current over-50 generation, meaning that the birthrate will be several times as high as the death rate for another 25 years. For the 25 years after that, the birthrate will still be around double the death rate. The population growth rate, which is the difference between the birth and death rates, will continue to be positive. Only when people now aged 0–25 reach the end of their life span will *their* grandchildren no longer outnumber them. Thus Equatoria's population will continue to grow for 50 years before it stabilizes, reaching a total of 12 million, 71 percent higher than its current level, before it stabilizes.

This is the meaning of population momentum. When a country has a history of rapid population growth, continued growth for the next several generations is virtually guaranteed, short of some massive Malthusian catastrophe that dramatically raises death rates. A more realistic projection for Equatoria might be that fertility rates, rather than falling instantaneously as in our hypothetical case, would take about a generation to reach replacement level. In that case, population would continue to grow for 75 years, finally stabilizing at a level that would be more than double the 2000 level.

The case of Equatoria is not merely an abstract example (see Box 15.1). As Figure 15.7 shows, the simplified population pyramid described is very close to the reality for most countries in Sub-Saharan Africa. (Use Figure 15.7 to visualize a future Africa in which all population age groups or **population cohorts** are at least as large as the present cohorts of young children.) Also recall that the medium projection for Africa in Table 15.2 indicated a doubling of population by 2050, consistent with our simplified example.

population cohort the group of people born within a specific period in a country.

Figure 15.7 Population Age Structures for Sub-Saharan Africa, Western Europe, and China, 2015



Source: United Nations, 2015.

If we turn to the population pyramid of Western Europe in Figure 15.7, it shows a completely different picture with a narrow base, and a shape where almost all generations except for the very oldest have approximately the same size. China's pyramid, also shown in Figure 15.7, gives a very clear illustration of a change in population momentum. It shows a sharp decline in the size of population cohorts born in the 1970s and early 1980s (currently aged 30–44) compared with the size of previous generations. This resulted from the very strict and coercive "one-child policy" implemented in those years, which enforced a sudden decrease in fertility rates.

But in the case of China we can observe that the population cohorts born in the late 1980s and early 1990s (currently aged 20–29) are larger in size than the previous cohorts, mirroring the size of the generation born in the 1960s and 1970s: this second "wave" corresponds to the children of these larger cohorts, born before the one-child policy. Even with a much lower fertility rate, just by the mere fact of their sheer size, this earlier generation gave birth to a young generation of about the same size as they were. The population momentum from the size of the generations from the 1960s and 1970s is, therefore, automatically replicated as a rippling effect into another generation born in the 1990s and 2000s. China is now entering the phase when the smaller cohorts from the 1980s are having their children, and the youngest generation (ages 0–19) can be seen to be smaller in size than the generation that immediately preceded them.

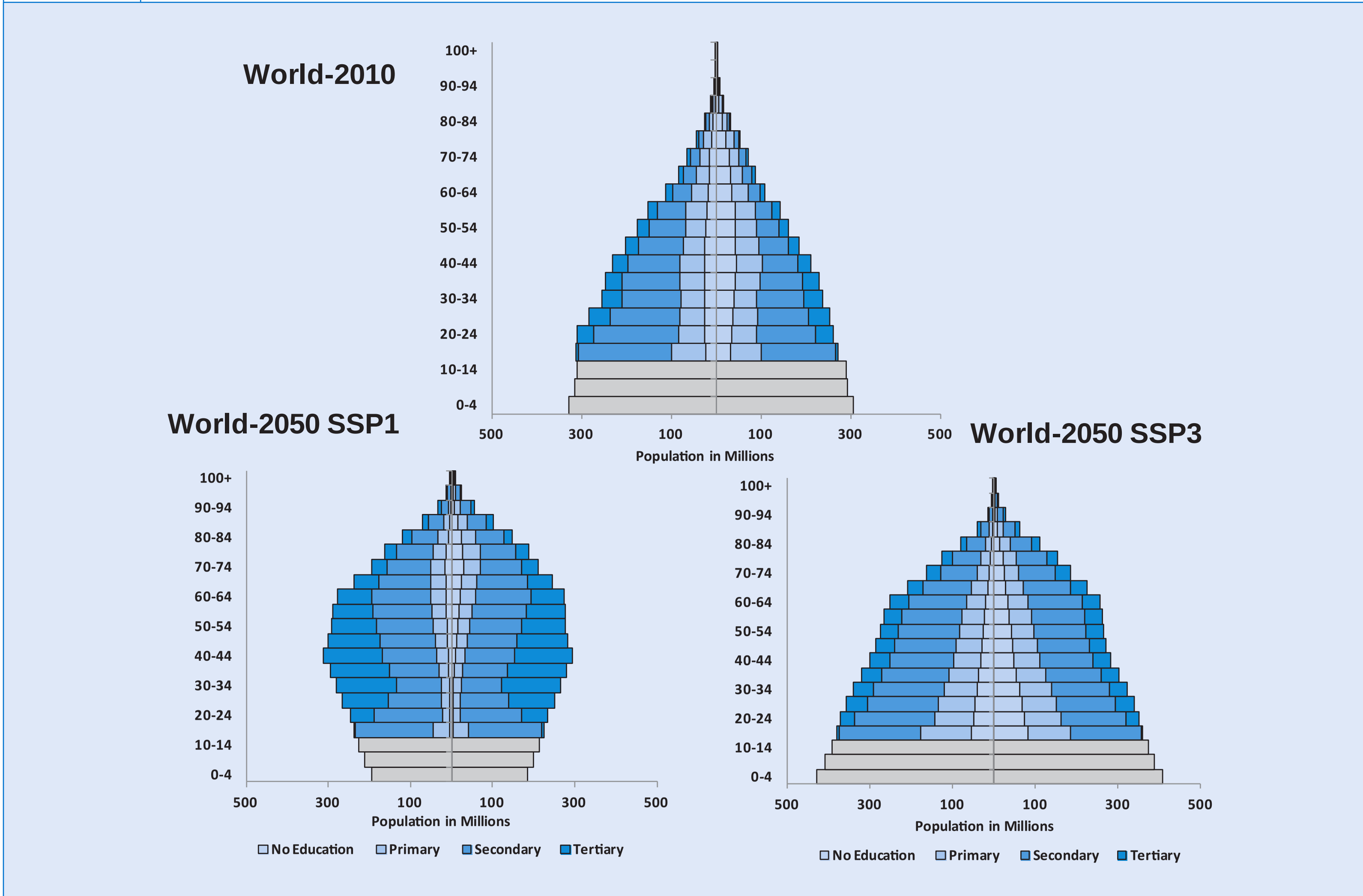
Population momentum makes substantial increase inevitable, but a huge difference remains between "low" and "high" forecasts for 2050 and beyond (see Figure 15.5). The critical variable in these differing projections is the rate of future fertility decline. If fertility falls rapidly throughout the developing world, the global population age pyramid could approach a more stable pattern within the next 35 years. If not, global population momentum will continue. This is shown by the two quite different forecasts for the world of 2050 shown in Figure 15.8. One is based on an assumption of relatively high education levels and low fertility; the other on an assumption of relatively low education levels and high fertility.

Box 15.1
RAPID POPULATION GROWTH STRESSES NIGERIA

Nigeria is the world's sixth most populous nation, with 167 million people. At the rate Nigeria is growing, in a quarter of a century 300 million people—a number equal to the present-day United States—will live in a country roughly the combined size of Arizona, New Mexico, and Nevada. The population growth rate in Nigeria is similar to that of other Sub-Saharan African countries, posing severe problems to governments as they struggle to keep up with resource and infrastructure demands. As a result, many governments have started to reverse pro-natalist policies that encouraged large families. In 2011, Nigeria made contraceptives free and stated official promotion of the advantages of small families. "Population is key," said Peter Ogunjuyigbe, a demographer at Obafemi Awolowo University in the small central city of Ile-Ife. "If you don't take care of population, schools can't cope, hospitals can't cope, there's not enough housing—there's nothing you can do to have economic development."

Source: E. Rosenthal, "Nigeria Tested by Rapid Rise in Population," *New York Times*, April 14, 2012.

Figure 15.8 Alternative Futures for World Population



Source: Lutz *et al.*, 2014.

Note: Scenario SSP1 assumes investment in high education and family planning. Scenario SSP3 assumes a continuation of current trends.

15.3 THE THEORY OF DEMOGRAPHIC TRANSITION

From the 1960s to the 1990s, the international community showed growing concern about rapid population growth, expressed at the third United Nations International Conference on Population and Development in Cairo in 1994. This conference adopted the ambitious goal of stabilizing world population at about 7.27 billion by 2015—an increase of roughly 30 percent over 1994 levels.

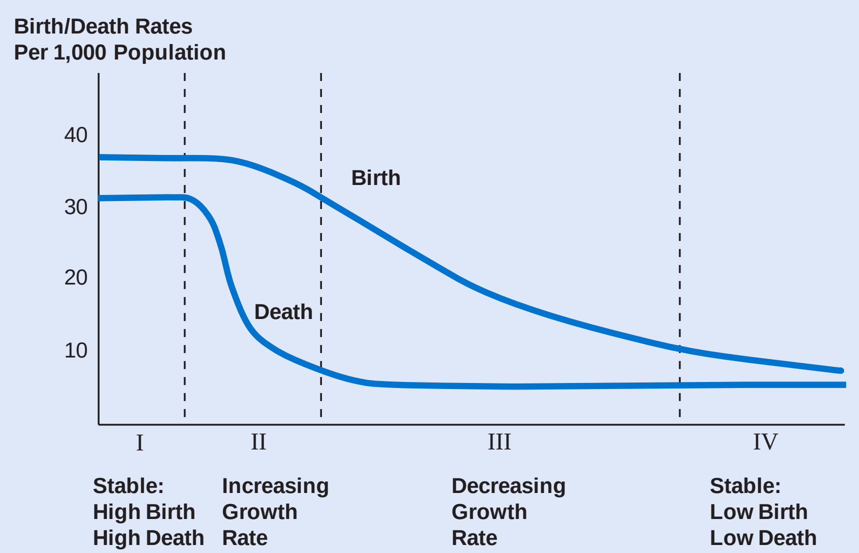
This objective obviously was not reached, since the world population reached 7.35 billion in 2015. Current medium-variant projections by the United Nations indicate a world population of 8.5 billion by 2030, a net addition of 1.23 billion people over 2015 levels, with growth continuing after that to reach a possible 10 billion by 2060 and 11.2 billion by 2100.[8] Certainly the task of supplying the needs of an extra 3 billion people is a daunting one. The course of population growth and fertility levels over the next 20 years will profoundly affect all the issues of food production, resource use, and pollution generation, which we consider in upcoming chapters. What, then, can an environmental or ecological economics analysis tell us about population policy?

demographic transition the tendency for first death rates and then birthrates to fall as a society develops economically; population growth rates first increase and eventually decrease.

Much thinking about the relationship of population to economic growth rests on the experience of Western Europe. Western Europe's situation is considered the final stage of a **demographic transition** from high to low birth and death rates. Figure 15.9 shows the pattern of this demographic transition.

In the first stage, corresponding to preindustrial Europe, both birth and death rates are high. Large families are common, but medical care is poor, and many children die young. On average, a family produces only two surviving children. Thus the population remains stable from generation to generation. These social conditions resemble in many ways the state of

Figure 15.9 The Demographic Transition



nature, in which birds and animals typically produce numerous progeny to offset high rates of predation and disease. It is a harsh but ecologically stable regime.

In the second stage industrialization takes off, as in nineteenth-century Europe. Death rates fall rapidly as standards of living, public health, and medical care improve. Birthrates remain high, however, because families still view a large number of children as valuable, both to work on the farm or in the factory (child labor is still legal and common) and as a form of old-age insurance (no social security institutions exist). Since net population growth rate is equal to the birthrate minus the death rate (the distance between the two lines in Figure 15.9), the result is a rapidly growing population.

Is growing population a good or bad thing for the country as a whole? If resources are abundant, the country's leaders may welcome it. A large labor force promotes rapid economic growth, making it possible to take advantage of unexploited resources and new technology. However, this period of rapid population and economic growth probably contains some self-limiting factors.

One such factor is the improvement in social conditions that is likely to accompany economic growth. This development, by no means automatic, often requires hard-fought battles for social and economic reform. Eventually, however, the country may achieve social changes characteristic of economically developed countries, including child labor laws, unemployment compensation, social security systems, private pension plans, and greater educational opportunity.

The third phase of the demographic transition corresponds to a changed social and cultural atmosphere. Smaller families are seen increasingly as more desirable by the most educated part of the population, and these new family values then spread to the rest of society. In this phase, economic opportunity costs of childbearing are more and more considered as a burden rather than a benefit. As greater opportunities arise, especially for women, family size shrinks (see Box 15.2). And, as indicated in Figure 15.9, during the third phase the population growth rate declines.

Figure 15.9 shows only the *rate* of population growth (the difference between birth and death rates). The total population, of course, is considerably larger in the third stage, so a lower *rate* of growth may still mean a higher net addition to population (gross annual population increase) each year. Population, as we have seen, could double or triple during this period of declining birthrates. But if birthrates continue to decline, eventually the country will reach the fourth and final stage of stabilized population with low birthrates and low death rates.

As a retrospective view of European history, the process of the demographic transition appears relatively benign. Despite the great hardships involved in the early stages, overall it appears that population growth, economic growth, and social progress went hand in hand and that population growth was eventually self-limiting. The Malthusian vision failed to be realized—on the contrary, larger populations typically led to better living conditions.

In both Europe and the United States, the third phase of the demographic transition, corresponding to the decrease of fertility rates (average number of children per woman), was strongly correlated with an improvement in living conditions. Indeed, that strong relationship between better economic conditions and lower fertility is universally observed, both in long-term trends and in comparative perspectives. Figure 15.10 shows this pattern for all countries in the world, with fertility rates (y-axis) generally falling with increasing GDP per capita (x-axis). This correlation was expressed by a famous remark made at the United Nations Population Conference in Bucharest in 1974 by India's minister of population: "development is the best contraceptive." Other analysts have noted that, more than the growth in GDP per capita itself, the improvement in other dimensions of human capital, including education (especially women's education) and health care (especially reproductive health), are the key determinants for a sharp decline in fertility rates (see Boxes 15.2 and 15.3).

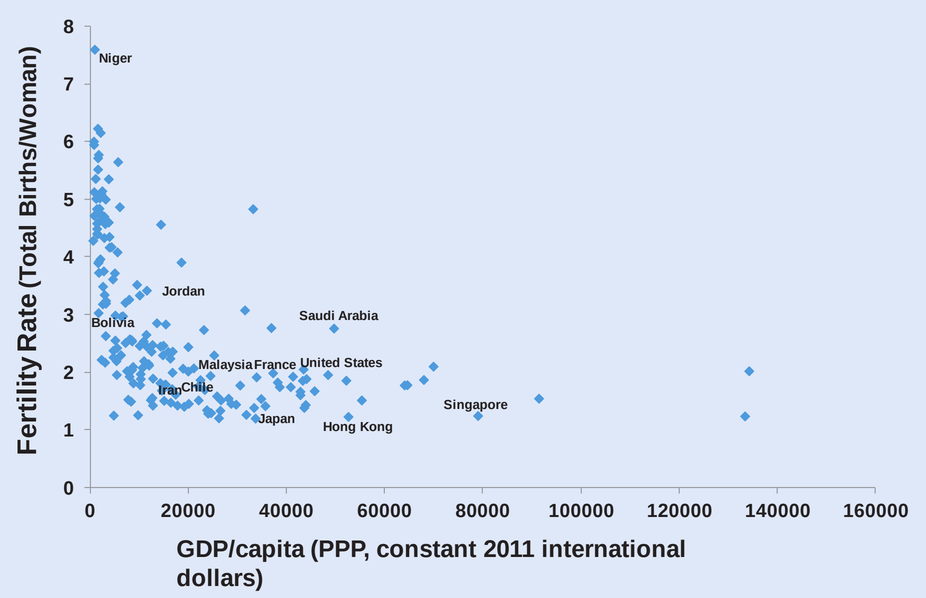
Box 15.2

WOMEN'S EMPOWERMENT AND THE FERTILITY TRANSITION

A key change in society that promotes a decrease of fertility rates is the increasing level of women's empowerment in terms of whom they marry, when they marry, and when they have children. Their degree of independence relative to the male members of their families (father, brother, husband) is positively correlated with the level of women's education and participation in the job market, allowing greater financial independence. Better educated women tend to marry later, have more knowledge about and access to contraception, use contraception more effectively, have greater autonomy in reproductive decision-making, and are more motivated to postpone childbirth because of the higher opportunity costs of unintended childbearing. In Ethiopia for instance, census data show that women without formal education have more than six children on average, whereas women with secondary or higher education have only two children. Even in cultural settings that are religiously conservative, high education levels for girls and women, accompanied by a health care system that makes contraception available, can lead to a rapid fertility transition, as suggested by the extraordinary demographic trajectory of Iran (see Box 15.3).

Sources: J. Bongaarts, 2010 "The Causes of Educational Differences in Fertility in Sub-Saharan Africa," *Vienna Yearbook of Population Research*, 8: 31–50; W. Lutz and V. Skirbekk, "How Education Drives Demography and Knowledge Informs Projections," in Lutz *et al.*, 2014.

Figure 15.10 Total Fertility Rate versus GDP per Capita, 2009



Source: World Bank, World Development Indicators, http://data.worldbank.org/data-catalog/world-development-indicators.

Notes: Countries with population over 5 million plotted. GDP = gross domestic product, PPP = purchasing power parity. PPP adjusts GDP to take account of price levels for domestically consumed goods and services.

Box 15.3 IRAN'S FERTILITY REVOLUTION

When the Shah was ousted by the Islamic revolution of 1979, the fertility rate in Iran was high, around six children per woman on average, a rate characteristic of the early stages of the demographic transition. The new regime, led by an assembly of very conservative clerics, suppressed all of the family planning programs that were in place. As a result, fertility rates rose even higher, to 7 children per woman. At those rates, population growth is extremely rapid (typically 3 percent per year, with more than a doubling of population each generation).

The census of 1986 resulted in the realization by government officials that population growth could not continue at this very high level without producing major negative consequences for economic development. Reluctantly, conservative Islamist leaders had to recognize that a strong family planning policy was an absolute necessity, and a national family planning program was launched in 1989. From then on, religious leaders actively supported the new program and the advantages of family planning were preached in the mosques. The spread of the national public health system to all regions of the country and at the village level meant that the program could be delivered effectively and efficiently to most women in the country. In Iran, free family planning is available within an hour's walk for around 90 percent of the population. However, what these clerics might not have anticipated is how quickly Iranian women would seize these new opportunities to realize the most rapid fertility transition ever recorded, from 7 children per woman in the early 1980s, to below replacement level, 1.9 children per woman in 2006.

Source: Mohammad Jalal Abbasi-Shavazi, Peter McDonald, Meimanat Hosseini-Chavoshi, *The Fertility Transition in Iran, Revolution and Reproduction*, Springer, London, 2006.

How well does the theory of demographic transition apply to present global population trends? Certainly the first two stages of the demographic transition theory apply well to the developing world's experience in the second half of the twentieth century. Death rates have fallen much faster than birthrates; fertility and population growth rates rose to historic highs between 1950 and 1975. Since then, strong evidence indicates that most countries have entered the third phase, with overall growth rates falling. In many respects though, currently developing countries are going through their demographic transition in a significantly different context than Europe's, and in much more adverse circumstances:

- The total population numbers in developing countries are much larger, unprecedented in history.
- In their expansion, Europe and the United States drew on the rest of the world for supplies of natural resources. The currently developed countries have disproportionately exploited the global environment's waste absorption capacities (contributing by far the highest proportion of greenhouse gas emissions, ozone-depleting chemicals, and other environmental pollutants). The developing world obviously will not have these options.
- There is significant uncertainty concerning the pace of fertility decline. Factors that contribute to fertility decline, such as education of girls and women, access to health care, and access to contraception, may be present in some countries but absent in others. Projections of population stabilization depend strongly on rapid fertility decline, which may or may not occur. Current fertility rates vary widely, with rates in Africa and some parts of the Middle East and Latin America still very high (see Figure 15.11).

- The rapid economic growth that accompanied population growth in Europe has occurred in some developing countries but not in others. Those in Africa, in particular, have experienced high population growth together with stagnant or declining output and food production per capita. In places where economic growth has been strong, its benefits have not "filtered down" to the poor, resulting in increased inequality and a greater absolute number of people living in extreme poverty. In the "dual economies" of many countries in Latin America and South Asia, modern urban development coexists with extreme rural poverty and huge slums surrounding major cities. Many people have not yet achieved the improved living standards that contribute to fertility decline.

These arguments suggest that "looking back" to the history of population and economic growth offers insufficient insight into the population-related issues of the next 40 or 50 years. Social, economic, and environmental factors intertwine with demographics. The impacts of

Box 15.4
U.S. POPULATION CONTINUES TO GROW

When we think of population problems, we tend to focus on rapid population growth rates in developing countries. But population is far from stable in the United States. Although Europe has completed the demographic transition to stable population levels, both natural increase and immigration keep the U.S. population growing. U.S. fertility rates are at replacement levels, but population growth since 1950 has generated large cohorts of people who are still in their reproductive years, creating significant continuing population momentum.

A larger increase in U.S. population occurred in the 1990s than in any other 10-year period in the country's history, surpassing even the baby boom decade of the 1950s. Population grew from 248.7 million to 281.4 million during the 1990s. In the decade between 2000 and 2010 the population grew another 27.4 million. The U.S. population reached 321 million in 2015.

U.S. population is projected to continue growing for at least the next three decades. According to the United States Census Bureau, projected U.S. population for 2025 will be 347 million, an increase of 66 million, or 23 percent, over 2000 levels. Projected population for 2050 is 398 million. While there is some uncertainty about the longer-term figures, these numbers indicate the continuing power of population momentum combined with immigration.

Since U.S. residents have the highest resource consumption and waste generation rates on the planet, the environmental impacts of consumption by these additional people will be much greater than that of a comparable number in a low-income country. Thus even though the projected U.S. population increase is only about 3 percent of likely global population growth, it has considerable significance for global environmental issues like greenhouse gas emissions.

An increased U.S. population will also put growing pressure on domestic land and resources. Urban and suburban sprawl, overdraft of water supplies, and air and automobile traffic congestion will all become more difficult to manage. In considering these various environmental issues, we should not forget the underlying importance of population. Population policy is clearly as relevant for the United States as it is for developing countries.

Sources: Population Reference Bureau, *2015 World Population Data Sheet* (Washington, DC, 2015); U.S. Census Bureau, *Largest Census-to-Census Population Increase in U.S. History as Every State Gains*, https://www.census.gov/newsroom/releases/archives/census_2000/cb01cn64.html;

U.S. Census Bureau, *2010 Census Brief, Population Distribution and Change, 2000 to 2010*,

https://www.census.gov/prod/cen2010/briefs/c2010br-01.pdf;

Population Reference Bureau, data finder http://www.prb.org/DataFinder/Geography/Data.aspx?loc=312.

population growth are not limited to developing countries; the United States faces significant continuing population growth based on a combination of natural increase and immigration (see Box 15.4). We cannot simply wait for the second, global process of demographic transition to play itself out. Rather, we must apply the best analysis and policy response possible to an issue of fundamental importance to the economic and environmental parameters of the twenty-first century.

15.4 POPULATION GROWTH AND ECONOMIC GROWTH

constant returns to scale a proportional increase (or decrease) in one or more inputs results in the same proportional increase (or decrease) in output.

per capita output the total product of a society divided by population.

law of diminishing returns the principle that a continual increase in production inputs will eventually yield decreasing marginal output.

capital shallowing a decrease in the availability of capital per worker, leading to reduced productivity per worker.

technological progress increases in knowledge used to develop new products or improve existing products.

capital formation addition of new capital to a country's capital stock.

natural resource limitations constraints on production resulting from limited availability of natural resources.

natural capital the available endowment of land and resources, including air, water, soil, forests, fisheries, minerals, and ecological life-support systems.

What does economic theory say about population? A typical economic model, the Cobb-Douglas production function, shows economic output as a function of labor input, capital input, and technological parameters:

$$Q_t = A_t K^{\alpha}_t L^{\beta}_t$$

where Q is total output, K is the capital stock, L is the labor force, and α and β are parameters related to the productivity of capital and of labor respectively, A reflects a given state of technology, and t indicates a particular time period. The values of α and β are assumed to be fractions between 0 and 1; if $\alpha + \beta = 1$, the function shows **constant returns to scale**. This means that if labor and capital inputs were both doubled, output would also double.

Suppose that we increase only one factor, labor. Output will also increase, but by a smaller percentage than labor input, because the exponent α is less than 1.[9] If labor is roughly proportional to total population, **per capita output** will decline. As more and more labor is added, the **law of diminishing returns** comes into play, giving smaller output boosts for each additional unit of labor input. Thus in a simple economic model, population increase alone would yield falling living standards. This is a result of **capital shallowing**, which means that each worker has less capital to work with and is thus less productive.

However, few economists would view this simple logic as an accurate representation of the effects of population growth. They would point to the capital stock variable K, noting that if K grows at a rate at least equal to that of L, output per capita will remain constant or rise. In addition, they would argue that we can safely bet that **technological progress** will increase the variable A over time, leading to greater output for each unit of labor or capital input. In this theoretical framework, provided that **capital formation** and technological progress are adequate, population and labor force growth can be accompanied by a rising standard of living.

What about the issue of **natural resource limitations**? We can modify the Cobb-Douglas production function to take account of **natural capital**—natural resources such as arable land and water for agricultural products, and minerals and fossil fuels as key inputs for all economic activities. If we denote natural capital by N and its productivity by the exponent γ, we get a revised equation:

$$Q_t = A_t K^{\alpha}{}_t L^{\beta}{}_t N^{\gamma}.$$

In this formulation, limitations on natural capital could cause diminishing returns even if labor and capital both increase. For example, if $\alpha = \beta = \gamma = 1/3$, a doubling of labor and human-made capital while natural resources remain constant would increase output by a factor of 1.59, leading to a fall in per capita output. This decline could still be avoided by sufficiently rapid technological progress, but the natural resource limitation would be a steady drag on output expansion.

There is some evidence that population growth can actually spur technological progress in some cases. Ester Boserup has argued that increased population pressure forces the adoption of more efficient agricultural techniques.[10] At least in the early stages of development, **economies of scale** may prevail; increasing population density may make it possible to develop more productive, larger-scale industry.

From the point of view of economic theory, then, population growth is inherently neither good nor bad. Its effects depend on the context in which it occurs. If economic institutions are strong, markets work well, and environmental **externalities** are not great, then population growth can be accompanied by higher living standards.

economies of scale an expanded level of output reduces per-unit production costs.

externalities an effect of a market transaction that changes the utility, positively or negatively, of those outside the transaction.

Does Population Growth Promote or Retard Economic Development?

Some analysts present a positive view of population growth both as a proof of successful advance in human technological skill and as a spur to further progress. One of the strongest proponents of this point of view, Julian Simon, suggested that we should welcome further population growth because human ingenuity will always overcome resource limitations and environmental problems.[11] Most economists and ecologists, however, reject this unqualified optimism. While acknowledging the importance of technological progress, most analyses of the overall impact of population growth present the issue as significantly more complex.

Economic theory recognizes a number of ways in which population growth may negatively affect economic development, including:

- **Increased dependency ratios.** Comparing the total number of people who are not working (primarily children and elderly) to the total population gives the dependency ratio for a country. We have seen that a growing population typically includes a high proportion of children. Families must spend more on supporting dependent children and, thus, have less to save, lowering the national saving rate. Higher spending on health and education is required, reducing funds available for capital investment. These effects tend to slow capital accumulation and economic growth. As population eventually stabilizes, dependency ratios are raised by a high proportion of elderly people, creating a different set of economic problems (see Box 15.5).

income inequality a distribution of income in which some portions of the population receive much greater income than others.

fixed factors factors of production whose quantity cannot be changed in the short run.

market failure situations in which an unregulated market fails to produce an outcome that is the most beneficial to society as a whole.

- **Increased income inequality**. A rapidly growing population creates an excess supply of labor, which brings down wage rates. High rates of unemployment and underemployment are likely, and a large class of extremely poor people receives no benefit from economic growth. This situation prevails in many Latin American countries as well as in India, where unemployed rural laborers migrate to large cities in search of jobs, creating vast slums surrounding city centers.
- **Natural resource limitations**. As previously noted, the inclusion of **fixed factors**, such as a limited supply of land or nonrenewable natural resources, in the production function can lead to diminishing returns to labor and capital. In general, economists have tended to assume that technological progress can overcome these limitations,[12] but as resource and environmental problems become more pervasive and complex, this assumption may not hold.
- **Market failure**. As we saw in the case of the open-access fishery discussed in Chapter 4, increased population accelerates depletion of the resource. Where private or social property rights are poorly defined, as in the African Sahel or the Brazilian Amazon, population pressure contributes to rapid desertification and deforestation. Also, where externalities such as air and water pollution are uncontrolled, population growth will worsen existing pollution problems.

This more complex view of the relationship between population and economic development has been addressed by Nancy Birdsall, who has suggested that "the long debate over population growth and development is entering a new phase. The emphasis is now on the interaction of rapid population growth with market failures."[13] In a review of economic studies, she points out that policy also plays a crucial role:

> Countries with higher rates of population growth have tended to see less economic growth. An analysis of the role of demography in the "Asian economic miracle" strongly suggests that changes in age structures resulting from declining fertility create a onetime "demographic gift" or window of opportunity, when the working-age population has relatively few dependents, of either young or old age, to support. Countries which recognize and seize on this opportunity can, as the Asian tigers did, realize healthy bursts in economic output.
>
> But such results are by no means assured: only for countries with otherwise sound economic policies will the window of opportunity yield such dramatic results. Finally, several of the studies demonstrate the likelihood of a causal relationship between high fertility and poverty. While the direction of causality is not always clear and very likely is reciprocal (poverty contributes to high fertility and high fertility reinforces poverty), the studies support the view that lower fertility at the country level helps create a path out of poverty for many families.[14]

In view of these recent observations, the question arises: Were the "positive" effects of population growth mainly characteristic of an earlier period in world history—what Herman Daly has referred to as the "empty world" stage, in which resources and environmental absorptive capacities are abundant relative to the scale of the human economy?[15] As global population rises to 10 billion or more, will the negative impacts become dominant? Answering these questions requires a consideration of a broader, more ecologically oriented perspective on population growth.

Box 15.5
FERTILITY DECLINE: IS THERE A BIRTH DEARTH?

Fertility, the most volatile variable in population projections, has declined worldwide, in many countries at a faster rate than expected. Does this mean that the "population problem" has gone into reverse? Some analysts think so. According to Phillip Longman, "Some people think overpopulation is one of the worst dangers facing the globe. In fact, the opposite is true. As countries get richer, their populations age and their birthrates plummet. And this is not just a problem of rich countries: the developing world is getting older fast. Falling birthrates might seem beneficial, but the economic and social price is too steep to pay."

Longman is really referring to two issues. One is in areas like Europe and Japan, where fertility rates have largely fallen below replacement levels. These countries face the prospect of a high dependency ratio of elderly people, with a diminished workforce to support them. Another is in the developing world, where a small number of countries are now approaching, or have reached, replacement fertility levels. Slower population growth is likely to be beneficial in these developing countries, lowering the child dependency ratio, and providing a higher proportion of working-age people to contribute to national productivity.

Lower fertility in India, for example, has gone hand in hand with improvement of women's status and economic well-being. Stabilizing populations also reduces pressure on scarce water supplies, arable land, and other resources. According to an expert panel on population issues, "fertility decline in high-fertility countries, by slowing population growth, makes many environmental problems easier to solve and development easier to achieve."

A different story is unfolding in Japan, where the birthrate has been in sharp decline since the 1950s and reached an all-time low of 1.3 live births per woman in 2010. If these trends continue, the population of Japan is projected to fall from 128 million to 95 million by 2050.

The elderly population has been growing steadily, so by 2040 more than a third of the population will be older than 65, and "there will almost be one centenarian to welcome each Japanese newborn." The problems of supporting an increasing number of elderly with a shrinking workforce also affect Europe and within the next several decades will have a major impact in China and other developing countries.

The problems of population stabilization, however, will have to be faced to prevent global population from growing indefinitely. As we have seen, even the lowest global projections show population increasing by well over a billion by 2025, and areas that still have high fertility, such as Africa, are likely to experience a doubling of population before 2050. Rates of population growth are slower in Latin America and Asia, but increases of 150 million and 1 billion, respectively, are projected for these areas. Thus Longman's prescription of trying to deal with the situation by policies to promote fertility seems unwise for the developing world, even if it might be relevant for Europe or Japan, where fertility has fallen well below replacement levels.

Sources: Longman, 2004; B. Crossette, "Population Estimates Fall as Poor Women Assert Control," *New York Times*, March 10, 2002; International Institute for Applied Systems Analysis, 2001; Population Reference Bureau, 2011; Eberstadt, 2012.

15.5 ECOLOGICAL PERSPECTIVES ON POPULATION GROWTH

Whereas the standard economic perspective sees no inherent limitations on population or output growth, the ecological approach is based on the concept of **carrying capacity**, which implies some practical limits to the population that can occupy a certain region. This certainly applies to animal populations in nature.

carrying capacity the level of population and consumption that can be sustained by the available natural resource base.

solar flux the continual flow of solar energy to the earth.

If, for example, a herd of grazing animals exceeds the land's carrying capacity, food will run short, many individuals will starve, and the population will be reduced to more sustainable levels. Predator species are even more tightly constrained in numbers, based on the available prey populations. Since animals live by consuming either plants or other animals, all life on earth depends on the ability of green plants to capture solar energy. The available **solar flux**, or flow of sunlight to the earth's surface, is thus the ultimate determinant of carrying capacity.

Can human populations escape the logic of carrying capacity? Certainly we have been very successful at stretching its limits. The use of artificial fertilizers has greatly increased agricultural outputs. Fossil fuel and nuclear energy provide far more power for industrialization than any solar flux that we currently capture, either directly through solar energy systems or indirectly through hydroelectric and wind power. Through these means, 7 billion people can live on a planet that a century ago supported only 1.5 billion.

However, this expansion of carrying capacity has a significant ecological cost. The extraction of large quantities of fossil fuels and mineral stocks causes environmental degradation both in production and through the waste products generated. Some of the wastes and pollutants are cumulative—their negative environmental effects build up over time.

A prime example is global climate change caused by burning fossil fuels. Soil erosion, depletion of aquifers, and buildup of long-lived toxic and nuclear wastes are also cumulative processes. While increasing the earth's carrying capacity today, we build up problems for the future. Many of these issues already pose major problems—How much worse will they become if a significantly larger population is consuming at higher per capita levels than today? How can we accommodate an additional 3 billion or more people with their food demands, carbon emissions, and other ecological impacts?[16]

Ecologists have identified three major areas in which current economic activities are systematically undermining the planet's long-term carrying capacity. The first is erosion and degradation of topsoil; topsoil losses worldwide are currently estimated at 24 billion tons annually, with nearly 11 percent of the world's vegetated land suffering moderate to extreme degradation. The second is overuse and pollution of fresh water supplies—a problem in virtually every country but especially China, India, and parts of the former Soviet Union, where it has reached critical levels. The third, and perhaps most serious, is the loss of biodiversity, with more species driven to extinction every year than at any time in the preceding 65 million years.[17]

Reviewing evidence gathered by dozens of scientists, Paul and Anne Ehrlich conclude that "there is considerable evidence that the enormous expansion of the human enterprise has already caused *Homo sapiens* to overshoot the long-term carrying capacity of Earth—the number of people that could be sustained for many generations without reducing the resources necessary to similarly maintain an equal population size in the future."[18]

The Impacts of Population, Affluence, and Technology

We can conceptualize the interrelationship of population, economic growth, and environment in an equation linking all three, which has come to be known as IPAT. The equation states that:

$$I = P \times A \times T$$

where:

I = Ecological impact (e.g., pollution or natural resource depletion)
P = Population
A = Affluence measured as output/population
T = Technology variable measuring ecological impact per unit of output

This equation is an **identity**, a mathematical statement that is true by definition. The right-hand side of the equation can be mathematically stated as follows:

identity a mathematical statement that is true by definition.

Population × Output / Population × Ecological Impact / Output.

"Population" and "Output" cancel each other out since they occur in both the numerator and the denominator, leaving only ecological impact—which is the same as the left-hand variable. Thus we cannot argue with the equation itself. The only questions are what the levels of the variables will be, and what determines them. What do we know about these questions?

We have seen that global population (*P*) is projected to increase by 2 billion, or about 30 percent, over the next 40 years, according to the UN medium-variant projection (see Table 15.2 and Figure 15.4). We also know that average per capita consumption (*A*) is steadily increasing throughout the world. If per capita consumption grows at 2 percent per year, which most development economists would view as a minimally satisfactory rate, it will increase by a factor of 2.7 in 50 years. The combined impacts of *A* and *P* will, therefore multiply the right-hand side of the equation by a factor of 3.5.

What about *T*? Improved technology could lower the ecological impact per unit of GDP—let us say by a factor of 2. This would still leave us with a significantly increased level of overall environmental impact (in terms of pollution and pressure on natural resources, land, water, forests, biodiversity, etc.). Given the current level of concern about environmental problems, this seems unacceptable. In order to project a lower overall environmental impact, we will need technological improvements that would lower the environmental impact by a factor of 4 or more.

Of course, a mathematical abstraction such as IPAT gives little insight into the specifics behind these very broad concepts. IPAT has been criticized because it assumes that *P*, *A*, and *T* are independent of one another when in fact they are related—the true nature of that relationship being a subject of controversy, as we have seen earlier. In a review on the theoretical implications of the use of the IPAT equation, Marian Chertow stresses:

> The chicken-and-egg nature of this debate—whether population or technology is a bigger contributor to environmental damage—is revealing. Does an increased population call for improved technology or does improved technology increase carrying capacity? (Boserup 1981; Kates 1997). Cross-country comparisons show that different types of ecological impacts present very different types of relation with the level of affluence (factor A) or economic prosperity as measured by GDP per capita. For instance, many types of air pollutants typically decrease with the level of GDP per capita, whereas CO_2 emissions increase with the level of affluence (Shafik and Bandyopadhyay, 1992).[19]

While the IPAT formulation has been mostly used by scientists (biologists, ecologists, engineers, etc.), it has faced strong criticism from social scientists and economists on the grounds that it covers up some basic issues concerning causes of population growth, consumption distribution, and the working of markets. The field of industrial ecology (discussed in Chapter 14) has focused its attention mostly on *T* in the IPAT equation, emphasizing the need for a major technological leap forward that would reduce *T* by a factor of 4 or even 10.[20]

One obvious concern is highly unequal consumption per capita throughout the world. The one-quarter of the world's population living in developed countries accounts for roughly three-quarters of global consumption. Poverty, a lack of basic health services, and poor education in many developing countries contribute to high population growth rates. This suggests a crucial need to focus on issues of inequality rather than only on total population or economic output.

Developed countries currently create the greatest environmental impact through their high per capita demand on resources, as well as pollution generation. If the developing countries succeed in raising living standards for their expanding populations—as China and other East Asian countries have done—their per capita demands for food and resources, as well as their pollution generation, will also increase. The combined effects of population and economic growth will significantly increase environmental pressures, in ways that will be rapidly unsustainable.

One obvious area in which the rate of population growth will have a major impact is climate change. According to one study, the slowing down of population growth from feasible reductions in fertility could yield the equivalent of at least one gigaton (billion tons) of reduction in carbon emissions by 2050, and significantly more in later years.[21] In an economic study of how population policies would impact carbon emissions reduction in developing countries, Wheeler and Hammer emphasize that population policies based on a rapid implementation of universal education for boys and girls would be a positive outcome for the developing world, regardless of climate mitigation, but that if in addition, it also contributes to mitigating climate change, this constitutes an important "win-win" strategy.[22]

Perhaps the economic and ecological perspectives can converge. Even if we cannot identify a fixed carrying capacity for the planet, it is clear that population growth at the levels that we are now experiencing increases virtually all resource and environmental stresses. This means that it is vital to have progress on all fronts—reducing population growth, moderating the growth of consumption, improving social equity, and introducing environmentally friendly technologies.[23]

15.6 POPULATION POLICIES FOR THE TWENTY-FIRST CENTURY

In recent years, the discussion of population policy has shifted. Past debate was dominated by the conflict between "optimists," who saw no problem in increasing population, and "pessimists," who predicted catastrophe. Now, elements of consensus are emerging. Most analysts accept that increasing population places extra stress on the environment and resources and agree that slower population growth in the future is essential. How can we accomplish this?

Countries have sometimes attempted to control population growth by government compulsion. The most prominent example of this is China's draconian "one-child" policy. Such policies have been discredited in most other countries both on human rights grounds and because they fail to alter basic incentives regarding fertility. Rather than changing people's desires to have children, they rely on penalties including forced abortions and sterilization of women. The policy, started in 1980, was phased out by the Chinese government starting in 2015, as it had created perverse effects and a high level of discontent among the population (see Box 15.6). After 35 years of implementation, the government gave in to the pressure from the Chinese population to relax this most rigid rule, and now allows couples to have a second child. The decision appears to have been driven by concerns that the country's low fertility rate would create a demographic crisis in the decades to come, with young generations not big enough to handle the costs of an aging population, and that eventually this situation could threaten the legitimacy of Communist Party rule.[24]

Similar drastic compulsory population policies have been used to a lesser extent in India, with several campaigns of sterilization in the rural areas, in the 1980s. A backlash against compulsory family-planning policies led to a reversal of approach in the mid-1990s. The Cairo Conference of 1994 (International Conference on Population and Development or ICPD), the last of the major international gatherings on the issue of population policy, reached a consensus of not considering population goals in numeric and quantitative terms any longer, but taking population as one of the dimensions of development policies, and focus on qualitative development goals. International donors shifted their focus to promoting general health care reform—including fighting HIV/AIDS and other deadly diseases. Revisiting the Cairo conference 20 years later, in 2014, the United Nations did not significantly change its language, and reassessed the importance of broader development goals without mentioning population policies.[25]

Box 15.6
THE PERVERSE EFFECTS OF COMPULSORY POPULATION POLICIES

The Chinese "one-child" policy created terrible side effects. Chinese culture favors male children over female children; sons typically take care of their elderly parents, while daughters, once married, only take care of their in-laws. Therefore, the "investment" in a daughter, especially for the poorest rural couples, could be seen as a net loss in the long term. This resulted in large numbers of infanticides of baby girls in the 1980s and, once the technology of ultrasound examinations was more broadly available in the 1990s and 2000s, large numbers of selective abortions of female fetuses. As a result men outnumber women by at least 33 million, according to the last 2010 census. The problem is likely to get worse, as it is projected that there will be a surplus of 40 to 50 million bachelors in China throughout mid-century. In addition, couples who have had two or even three children in contravention of the law have often been forced to hide these children in the countryside, often with older family members. It is estimated that at least 13 million children in China have not been registered and do not legally "exist" and therefore have no access to education or health services.

Selective abortion of female fetuses, as well as baby girl infanticides, are not phenomena limited to China. This pattern is also observed in other countries (notably in India, Pakistan, Bangladesh, Indonesia, and Nigeria), and it has been estimated that between 1970 and 2010, more than 125 million women have been "missing"—through abortion, infanticide, or neglect resulting in untimely death—throughout the world and that this number is expected to peak at 150 million in 2035.

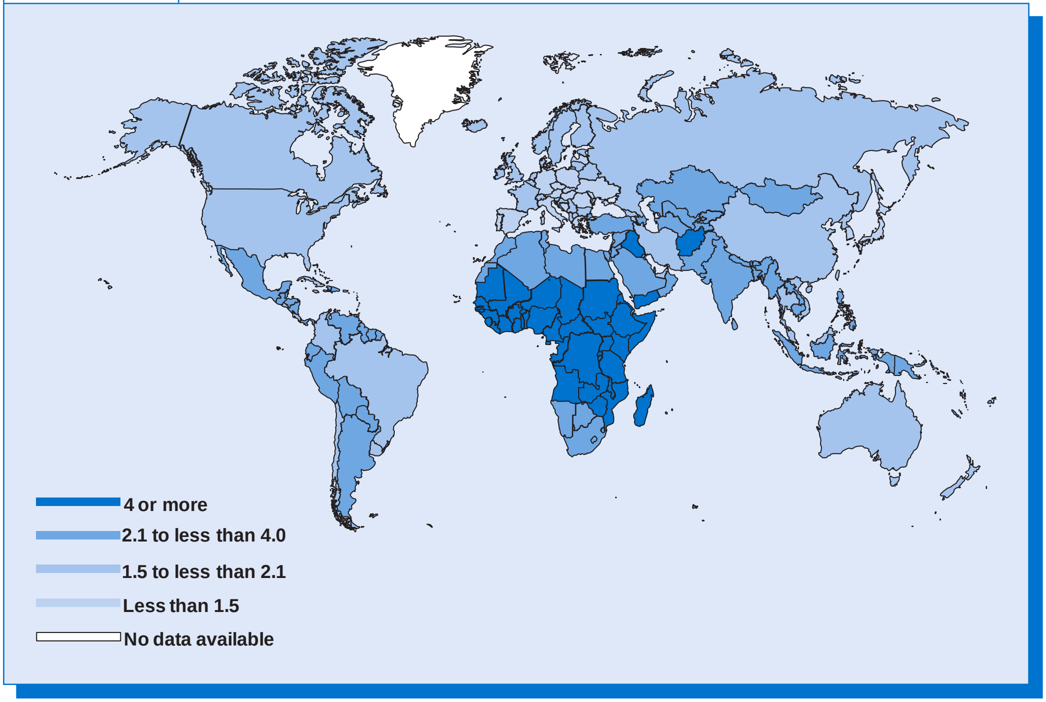
Sources: Taylor, 2015; John Bongaarts and Christophe Guilmoto; "How Many More Missing Women? Excess Female Mortality and Prenatal Sex Selection, 1970–2050," *Population and Development Review*, 41(2): 241–269, June 2015; Stephanie Gordon, "China's Hidden Children," *The Diplomat*, March 12, 2015, http://thediplomat.com/2015/03/chinas-hidden-children/.

Critics argue that by making fertility decline an incidental by-product of the millennial goals agenda rather than an explicit goal, the Cairo program has weakened the political and financial backing for population stabilization efforts. As shown in Figure 15.11, fertility rates remain very high in Africa as well as in parts of Asia and Latin America. With the potential for a doubling of the population of Africa between now and 2050 and a quadrupling by the end of the century (as shown in Table 15.2), critics suggest that the "population-neutral" language and policy used by the UN since the 1990s should be reconsidered.[26]

A few African countries have recently experienced faster fertility decline, including the island of Mauritius and the North African countries of Tunisia and Morocco, but moderating population growth would require a global concerted effort at the level of the whole continent. It is not necessary to apply coercive policies with the perverse effects they had on human rights, such as in China. The experience of several countries (including Iran) shows that birthrates can fall rapidly when people—especially women—reach higher levels of education and literacy and enjoy better employment opportunities and access to family planning. Significant voluntary reduction in the birthrate in many East Asian countries as well as in many parts of India has resulted from higher levels of basic education, health care, and job security.[27] There is no inherent reason why African countries should not follow a similar path, but this depends on effective development policies, including specific attention to health, education, women's empowerment, and contraceptive availability.

In analyzing which population policies are most effective, Nancy Birdsall focuses on the link between high fertility and poverty and the resulting vicious circle of negative social and environmental outcomes. She identifies a significant range of policies that can help both to

Figure 15.11 Total Fertility Rates (births per woman), 2010–2015



Source: United Nations, 2015.

slow population growth and to improve economic efficiency and output. Prominent among these are the promotion of education and other social programs, improvement in the status of women, and improved nutrition and health care, including the availability of contraception.[28]

All these policies tend to lower fertility rates and are identified by Birdsall as "win-win" policies—policies that benefit both the economy and the environment through voluntary moderation of population growth. Sound macroeconomic policies, improved credit markets, and improved conditions for agriculture are also important in promoting broad-based growth and poverty reduction, which in turn is critical for population/environment balance.

Such policies are essential for averting serious environmental and social breakdown in many developing countries. As people struggle to respond to higher demands on the land, slower population growth allows crucial breathing space—time to innovate and adapt. Higher population growth rates can push rural communities over the edge into neo-Malthusian collapse—not because of an absolute limit on carrying capacity but because the means and incentives to adopt new techniques were not forthcoming in time.

Urban areas, where population growth is most rapid due to a combination of natural increase and migration, often experience major social and infrastructure problems. Urban populations in Asia and Africa are projected to double over the next 30 years.[29] Inadequate housing and sanitation, congestion, air and water pollution, deforestation, solid waste problems, and soil contamination are typical of large cities in developing countries. Attempts to respond to massive social and environmental problems in cities are made more difficult by continuing rapid and unplanned growth. Moderation of overall population growth will have to be an essential component of efforts to achieve urban sustainability.[30]

Population growth was a major factor in shaping development patterns during the second half of the twentieth century and will continue to play a central role during the first half of the twenty-first. The differing perspectives of economists, ecologists, demographers, and other social theorists can all contribute to the development of effective policies aimed at population stabilization and an appropriate population/environment balance.

In later chapters, we use this overview of population as our basis for examining specific stresses associated with growing population and higher consumption levels—in agriculture, energy use, demands on natural resources, and pollution generation. In Chapter 22, we return to the issue of a sustainable global future for a growing human population.

Summary

Global population grew very rapidly during the second half of the twentieth century. Although population growth rates are now slowing, total annual additions to global population are still close to all-time highs, with a global population of 7.3 billion in 2015. Growth is projected to continue for at least the next three decades, reaching a level of about 9 billion by 2050, with some projections as high as 11 billion or more by 2100. More than 90 percent of the projected growth will be in the developing countries of Asia, Africa, and Latin America.

Population projections offer no certainty about actual future numbers, but the population momentum phenomenon guarantees significant further growth. Currently, average fertility rates (number of children per woman) are still high throughout the developing world. Although fertility rates are generally falling, it will be decades before the population stabilizes. Some projections based on more rapid fertility decline see global population stabilizing at about 8.5 billion by 2050, and declining thereafter.

In Europe, the demographic transition from rapid population growth to relatively stable population has been achieved. In the United States, growth continues due to both population momentum and annual immigration. In the developing world, the demographic transition is far from finished, and significant uncertainty remains about future birthrates. Economic growth, social equity, access to contraception, and cultural factors all play a role.

The economic analysis of population growth emphasizes the potential of other factors, such as technological progress, to offset the effects of population growth. Under favorable conditions for economic and technological progress, population growth may be accompanied by rising living standards. However, rapid population growth accompanied by social inequity and significant environmental externalities may lead to a decline in living standards.

An ecological perspective recognizes more stringent limits to the population carrying capacity of regional and global ecosystems. Greater population increases the demand for materials, energy, and natural resources, which in turn increases pressures on the environment. Given the extent of existing environmental damage, especially where this damage is cumulative or irreversible, the challenge of providing for significantly larger populations poses severe challenges to the earth's ecosystems.

Compulsory population control policies generally fail to alter basic incentives regarding fertility. More effective population policy measures include improved nutrition and health care, greater social equity, women's education, and availability of contraception.

Key Terms and Concepts

capital formation

capital shallowing

carrying capacity

constant returns to scale

demographic transition

dependency ratios

economies of scale

exponential growth

- externalities
- fertility rate
- fixed factors
- gross annual population increase
- identity
- income inequality
- law of diminishing returns
- market failure
- natural capital
- natural resource limitations
- neo-Malthusian perspective
- per capita output
- population age profile
- population cohort
- population growth rate
- population momentum
- replacement fertility level
- solar flux
- technological progress

Discussion Questions

1. What criteria would you use to evaluate the argument between the neo-Malthusians, who see population growth as the major problem facing humanity, and those who argue that population growth is a neutral or even positive factor for economic development? How would you assess the relative urgency of population concerns in the United States (population growth rate 0.7 percent per annum), India (1.9 percent per annum), and Kenya (3.3 percent per annum)?
2. "Every extra mouth brings with it an extra pair of hands. Therefore, we do not have to worry about growing population." Relate this statement to the more formal economic analysis of labor force and production. To what extent is the statement true? To what extent is it misleading?
3. The concept of carrying capacity is a useful one for the ecological analysis of animal and plant populations. Is it also useful for the analysis of human population growth? Why or why not?

Notes

1. United Nations, 2015, Medium Variant.
2. A given population P growing at 2 percent per year means that the next year this population will be 1.02*P, the year after that 1.02*(1.02*P) = $(1.02)^2$P, and so on and so forth. . . . the thirty-fifth year the population will be $(1.02)^{35}$ P = 2P. The population has doubled in 35 years.
3. Ehrlich, 1968; Ehrlich and Ehrlich, 1990, 2004.
4. United Nations, 2015.
5. Lutz *et al.*, 2014
6. With a growth rate of 3 percent per year, the population doubles in 25 years: $(1.03)^{25} = 2.09$. Using the "rule of 70," 25 = 70 / x and x = 70 / 25 or about 3 percent.
7. Population Reference Bureau, 2015.
8. United Nations, 2015.
9. If, for example, $\alpha = \beta = 1/2$, then a doubling of labor alone would increase output by a factor of 1.414. A doubling of both labor and capital would increase output by a factor of 2.
10. Boserup, 1981.
11. Simon, 1996.
12. See, for example, Solow, 1986.

13. Birdsall, 1989.
14. Birdsall *et al.*, 2001.
15. Daly, 1996, chap. 2.
16. On the relationship between population and other environmental issues, see, for example, Ryerson, 2010.
17. Ehrlich *et al.*, 2003; Postel, 2003.
18. Ehrlich and Ehrlich, 2004.
19. Chertow, 2000.
20. Weizsäcker *et al.*, 1997.
21. O'Neill *et al.* 2010.
22. Wheeler and Hammer, 2010.
23. Cohen, 1995; Engelman, 2008; Harris *et al.*, 2001, part IV; Halfon, 2007.
24. Taylor, 2015.
25. Population and Development Review, Cairo+20: the UN on Population and Development beyond 2014
26. Robert Engelman, "Africa's Population Will Soar Dangerously Unless Women Are More Empowered," *Scientific American*, February 1, 2016, http://www.scientificamerican.com/article/africa-s-population-will-soar-dangerously-unless-women-are-more-empowered/.
27. The cases of China and Kerala are reviewed in Sen, 2000, 219–224. On India, see Pandya, 2008.
28. See Birdsall, Kelley, and Sinding, 2001; Engelman, 2008; Halfon, 2007; Singh, 2009.
29. United Nations, 2015.
30. See Harris *et al.*, 2001, part IV.

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Web Sites

1. **www.prb.org.** Homepage for the Population Reference Bureau, which provides data and policy analysis on U.S. and international population issues. Its World Data Sheet provides demographic data for every country in the world.

2. **www.un.org/esa/population/unpop.htm.** Web site for the United Nations Population Division, which provides international information on population issues including population projections.

3. **www.populationconnection.org.** Homepage for Population Connection, a nonprofit organization that "advocates progressive action to stabilize world population at a level that can be sustained by Earth's resources."

CHAPTER 16

Agriculture, Food, and Environment

Contributing author Anne-Marie Codur

Chapter 16 Focus Questions

- Can we produce enough food for a growing global population?
- Are agricultural production systems degrading the environment?
- What are the impacts of new agricultural technologies?
- How can we develop a sustainable agricultural system for the future?

16.1 FEEDING THE WORLD: POPULATION AND FOOD SUPPLY

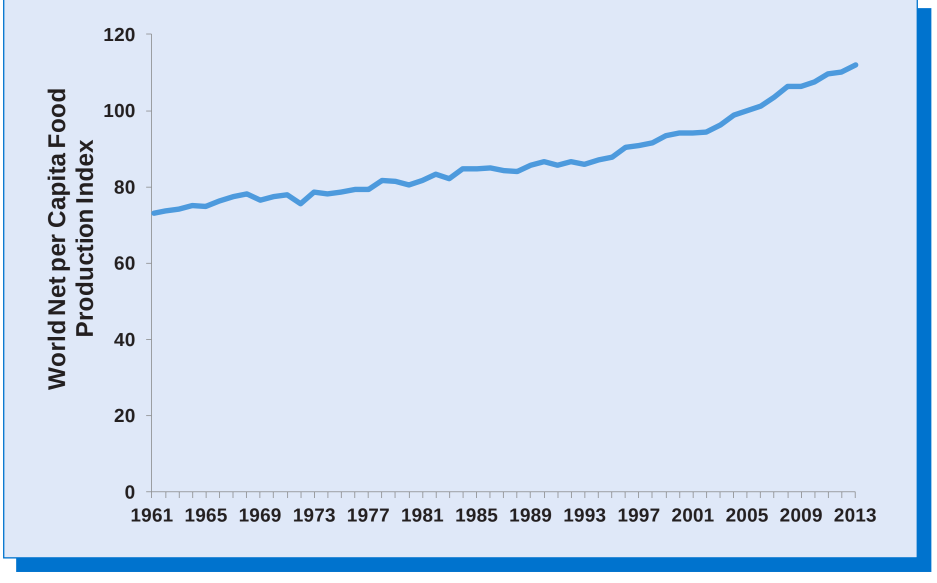
Food supply constitutes a fundamental relationship between any human society and its environment. In the wild, animal populations wax and wane based largely on food availability. For many centuries, human numbers were also linked closely to food abundance or scarcity. In the past two centuries, increasingly productive agricultural technology has spurred the rapid increase in human population that we discussed in Chapter 15.

Despite unprecedented population growth, average world per capita food production has risen steadily for the past six decades (Figure 16.1). Many economic theorists assert, based on this trend, that history has disproved the **Malthusian hypothesis** (discussed in Chapter 2) that population would outrun food supply. Before we dismiss concerns over food limitations, however, we must consider several factors that cast a different light on the issues of population, agriculture, and the environment:

Malthusian hypothesis the theory proposed by Thomas Malthus in 1798 that population would eventually outgrow available food supplies.

- *Land Use*. In the period following World War II, agricultural land use expanded considerably, but the expansion appeared to end around 1990 (see Figure 16.2). The land most suitable for agriculture is already being farmed, and most remaining lands are marginal in quality. Also, urban and industrial encroachments are cutting into agricultural land, some agricultural lands are being lost to degradation, and available farmland per person is steadily decreasing as population continues to grow (Figure 16.3). To feed the world better, we must increase productivity on this shrinking per capita acreage.

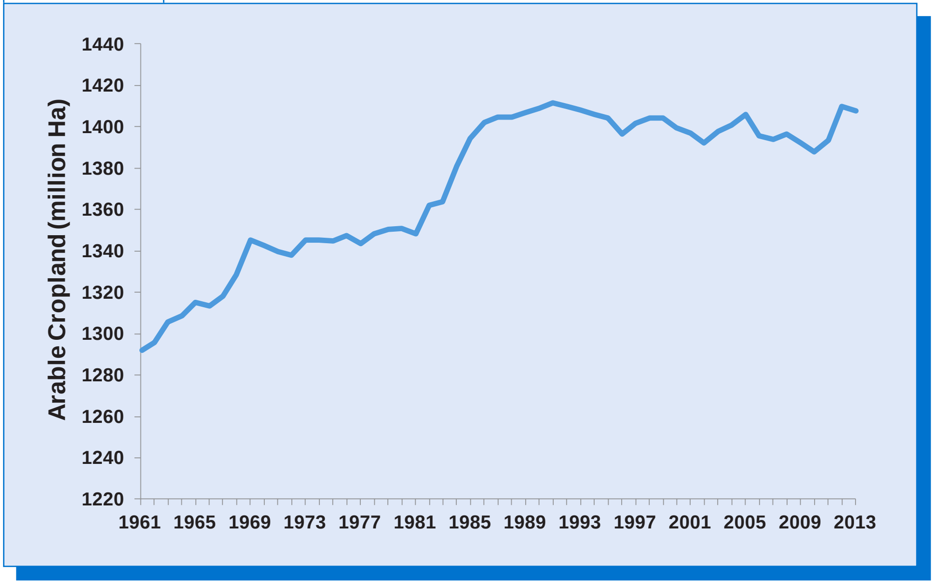
Figure 16.1 World Food Production per Capita, 1961–2013



Source: FAOSTAT, Food and Agriculture Organization of the United Nations, Statistics Division, http://faostat3.fao.org/.

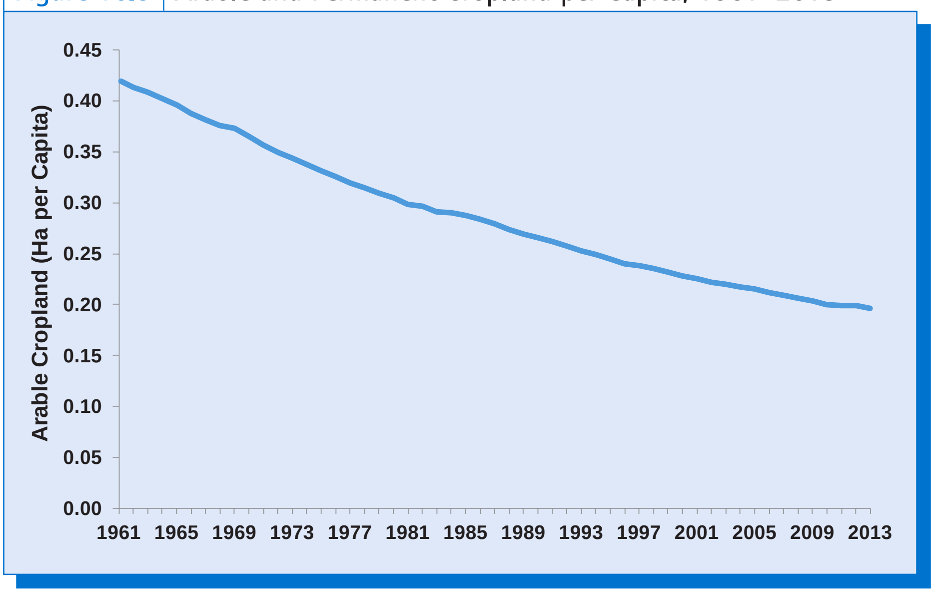
Note: Production quantities of each commodity are weighted by average international commodity prices and summed for each year. (Net per Capita Production Index: 2004 – 2006 = 100.)

Figure 16.2 Total World Arable and Permanent Cropland, 1961–2013



Source: FAOSTAT, Food and Agriculture Organization of the United Nations, Statistics Division, http://faostat3.fao.org/.

Figure 16.3 Arable and Permanent Cropland per Capita, 1961–2013



Source: FAOSTAT, Food and Agriculture Organization of the United Nations, Statistics Division, http://faostat3.fao.org/.

- *Inequalities in Food Distribution.* On average, enough food is produced to provide an adequate diet for everyone on earth. In practice, however, many low-income areas suffer from a **nutritional deficit**. The United Nations Food and Agriculture Organization estimates that in 2014–2016 about 795 million people, or one in nine of the global population of 7.3 billion people, were suffering from chronic undernourishment.[1]

- *Environmental Impacts of Agriculture*. As agricultural land use has expanded, more marginal and fragile lands have come into cultivation. The result is increased erosion, deforestation, and loss of wildlife habitat. Erosion and depletion of nutrients in the soil mean that a **renewable resource** is being turned into a **depletable resource**, and soil fertility is being "mined" over time. Increased irrigation, crucial to modern agriculture, also brings many environmental problems in its wake, including salinization, alkalinization, and waterlogging, as well as overdraft of groundwater and pollution of surface water.

nutritional deficit the failure to meet human demands for basic levels of nutrition.

renewable resources resources that are regenerated over time through ecological processes, such as forests and fisheries, but can be depleted through exploitation.

depletable resource a renewable resource that can be exploited and depleted, such as soil or clean air.

biodiversity (biological diversity) the maintenance of many different interrelated species in an ecological community.

Chemical fertilizer and pesticide use leads to runoff that pollutes land and water, while methane, nitrous oxide, and other agricultural emissions contribute to global climate change. Depletion of **biodiversity** and the creation of "super-pests" resistant to pesticides are also results of intensive agriculture. At a minimum, the management of these problems is an important issue in the economics of agriculture. More broadly, these environmental issues raise questions about the global agricultural system's capacity to sustain growing populations without unacceptable environmental damage.

These factors contribute to a more sophisticated perception of the problems involved in feeding an expanded world population. Rather than focusing on the simple dichotomy of population and food, we must examine interactions between population, per-capita food consumption, and the environment.

16.2 TRENDS IN GLOBAL FOOD PRODUCTION

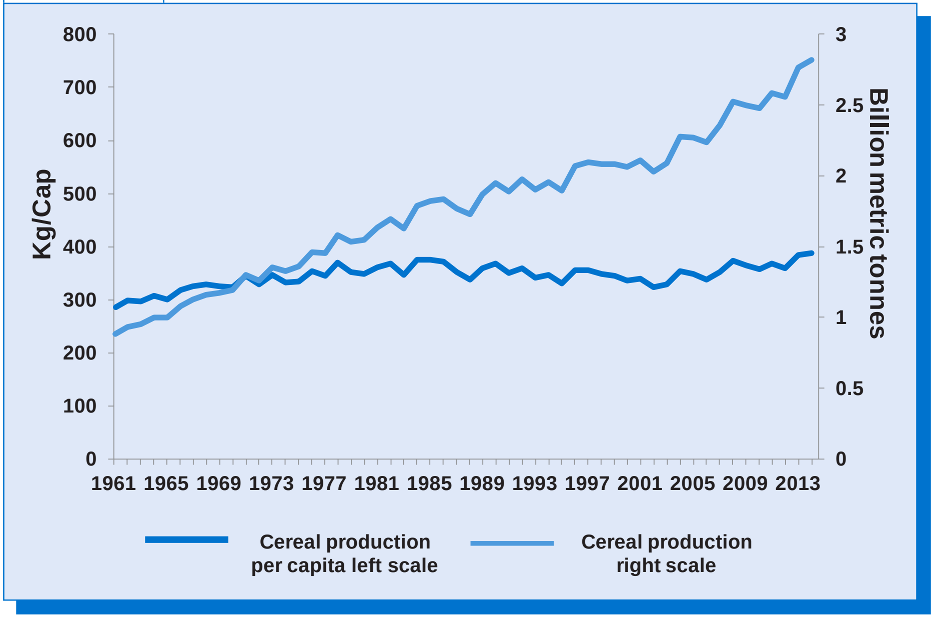
First, let us take a more careful look at the trends in global food production. Figure 16.4 shows trends for total and per capita production of grains. Grain, or cereal, output is easily measured and is significant because it provides the basis for the global diet, especially in poorer countries. Grain consumption is about half of food consumption worldwide and up to 70 percent in many developing countries.

The total output of grains rose from 1961 to 2014, but the per capita production figures tell a different story. From 1961 to 1985, output per capita increased slowly but steadily. After 1985, while total output continues to grow, per-capita output no longer increases. How can we evaluate this pattern of slowing or halting growth in per capita grain consumption? Does it indicate that we are reaching limits on supply capacity, or simply a change in demand patterns?

elasticity of supply the sensitivity of quantity supplied to prices; an elastic supply means that a proportional increase in prices results in a larger proportional change in quantity supplied; an inelastic supply means that a proportional increase in prices results in a small change.

From an economic perspective, the main question is one of price. If, indeed, agriculture experiences supply limitations, we would expect to see rising food prices as demand grows. The simple supply and demand analysis in Figure 16.5 shows this principle. Where **elasticity of supply** is high, as in the left half of the graph, demand increases from D_1 to D_2 with no significant upward pressure on price. With inelastic supply, in the right-hand portion of the graph, rising demand (D_2 to D_3) causes a sharp upward move in price.

Figure 16.4 World Grain Production, Total and per Capita, 1961–2014



Source: FAOSTAT, Food and Agriculture Organization of the United Nations, Statistics Division, http://faostat3.fao.org/.

As shown in Figure 16.6, before 2006 there was no sustained increase in prices for cereal crops. Taking inflation into account, real food prices declined from the 1960s through the early 2000s. Global trends changed, however, starting in 2006. Food prices started to rise, and with the onset of the "food crisis" in 2008, prices reached dramatically higher levels, which led to crises and food riots in many countries. After falling back somewhat in 2009 and 2010, food prices again reached historic highs in 2011 and 2012, then decreased in 2013–2016, but remained well above early-2000s levels

Figure 16.5 Elastic and Inelastic Food Supply

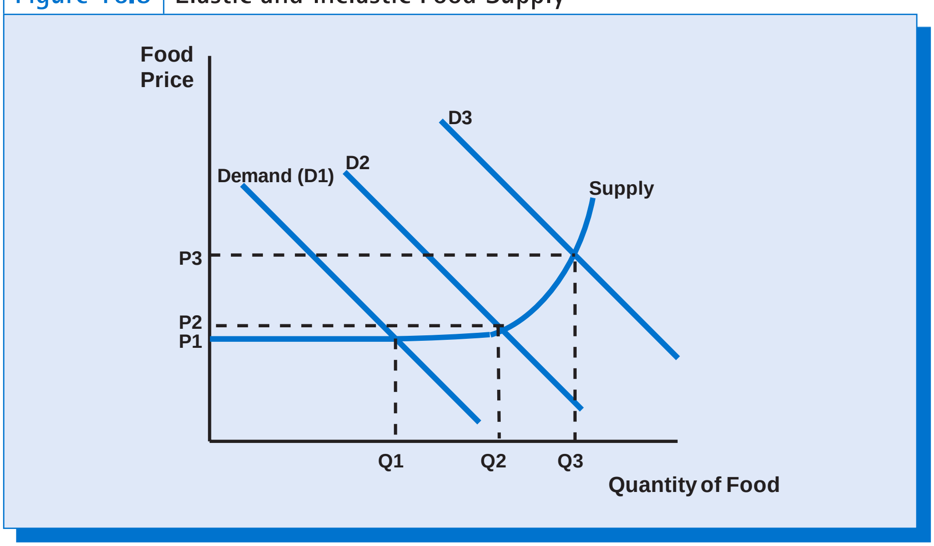
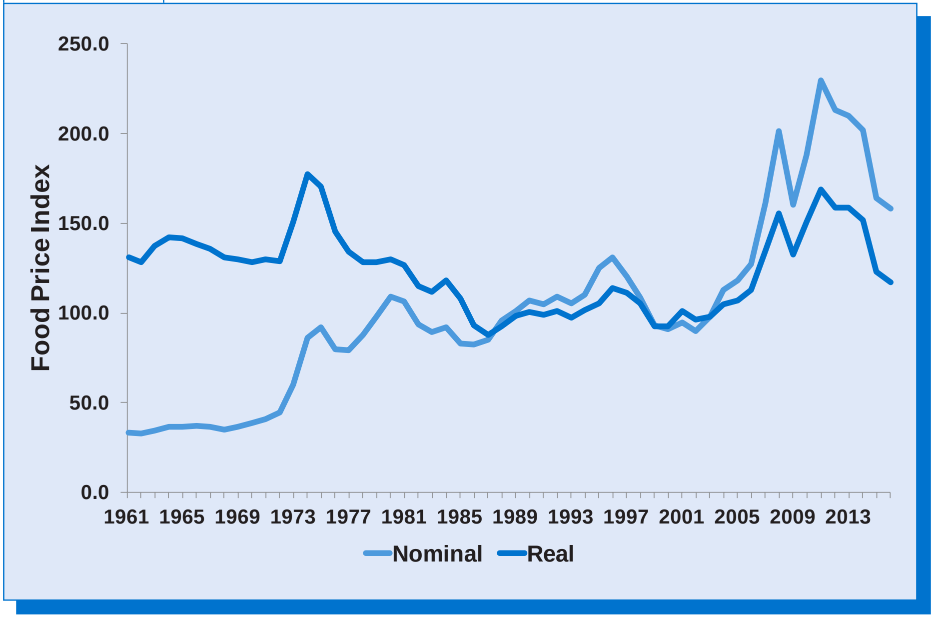


Figure 16.6 FAO Food Price Index, 1961–2016



Source: FAOSTAT, Food and Agriculture Organization of the United Nations, Statistics Division, http://www.fao.org/worldfoodsituation/foodpricesindex/en/.

Note: Prices for each commodity group are weighted by average export shares for 2002–2004. (Index: 2002 – 2004 = 100.)

Increased food prices are attributable in part to a growing "global middle class" with higher demands for meat and other luxury food products and in part to demand for **biofuels**, which compete with food crops for limited arable land. Since the U.S. government mandated use of ethanol in fuel, corn ethanol as a share of U.S. corn production has risen from about 5 percent in 2000 to 40 percent by 2012, representing an increase in demand that has significantly increased the price of corn exports (Figure 16.7).[2]

biofuels fuels derived from crops, crop wastes, animal wastes, or other biological sources.

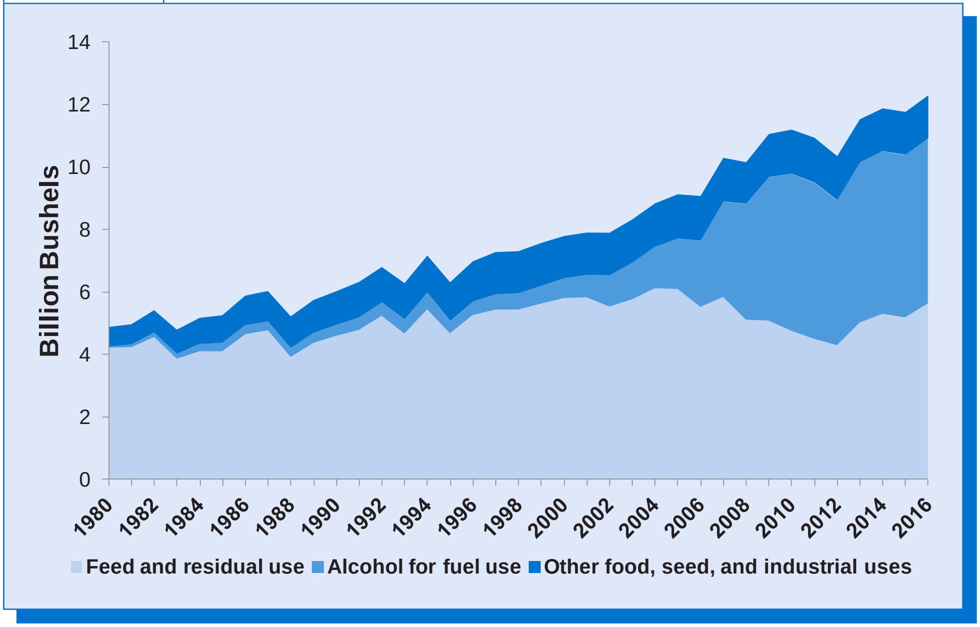
price volatility rapid and frequent changes in price, leading to market instability.

At the same time, new land for agriculture has become scarce. The steady increase in land in cultivation from the 1950s to the 1980s, which helped to accommodate growing world food demand, appeared to reach its limits around 1990, and since then there has been no net increase in world arable area (see Figure 16.2). In many developing countries, the poor bear the greatest burden of higher food prices, increasing the problem of inequality of distribution. In addition, environmental impacts of agriculture have an unequal effect, since the marginal lands farmed by the poor suffer the greatest damage from erosion and other environmental problems.

Combined with rising food prices, these trends indicate continuing problems with food security in the developing world. According to the Food and Agriculture Organization of the United Nations (FAO), "[food] **price volatility** makes both smallholder farmers and poor consumers increasingly vulnerable to poverty."[3]

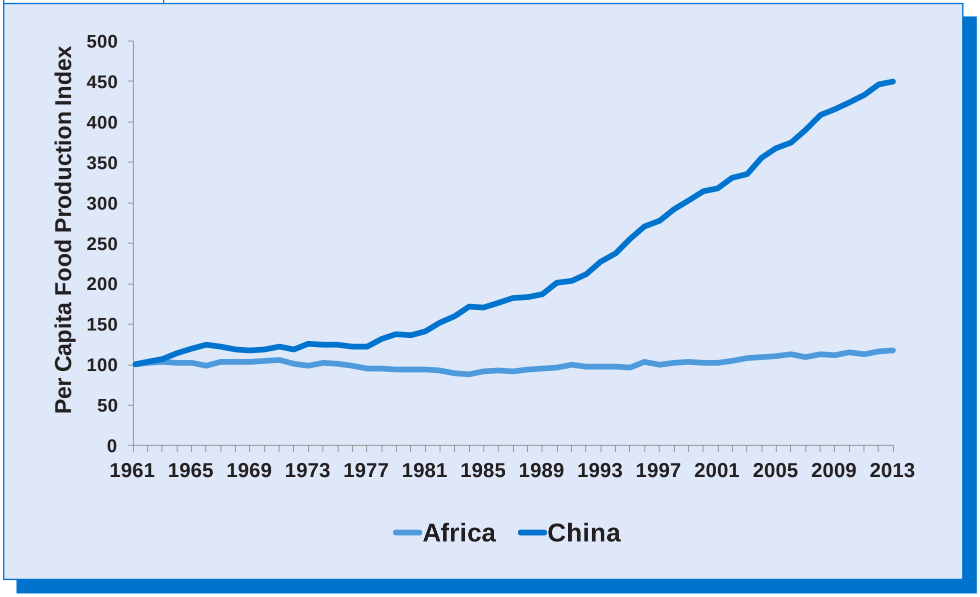
Again, there are significant country and regional differences. Considering per capita food production indices, which show a weighted average of food production per person, we can see significant contrasts. In China, per-capita food production has more than doubled since

Figure 16.7 U.S. Domestic Corn Use, 1980/1981–2016/2017



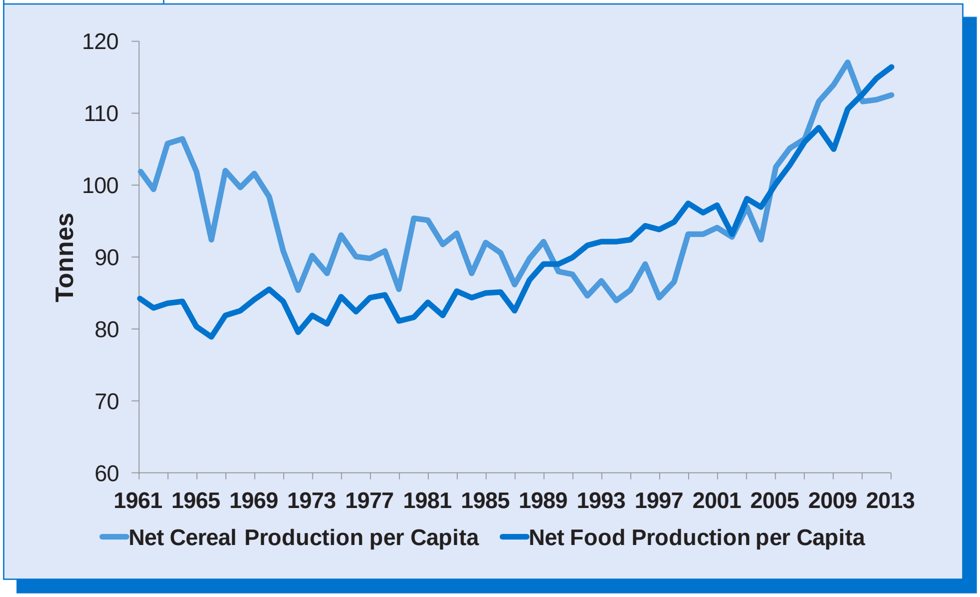
Source: U.S. Department of Agriculture, http://www.ers.usda.gov/topics/crops/corn/background.aspx.

Figure 16.8 Per Capita Food Production Indices for China and Africa, 1961–2013



Source: FAOSTAT, Food and Agriculture Organization of the United Nations, Statistics Division, http://faostat3.fao.org/.

Figure 16.9 Per Capita Food and Cereal Production Indices for Least Developed Countries, 1961–2013



Source: FAOSTAT, Food and Agriculture Organization of the United Nations, Statistics Division, http://faostat3.fao.org/.

Note: Production quantities of each commodity are weighted by average international commodity prices and summed for each year. (Net Per Capita Production Index: 2004 – 2006 = 100.)

1990, while in Africa it has increased much more slowly (Figure 16.8). For the world's 43 least-developed countries, there has been an increase in food production indices (a weighted average of different crops) since 1990, a significant improvement after a long period of stagnation or decline (Figure 16.9).

Land Use and Equity Issues

The issue of unequal distribution is linked to that of land use. We have already noted that most good agricultural land is currently in production. In a market economy, land will generally be used for the highest-valued crop, as shown in Figure 16.10.

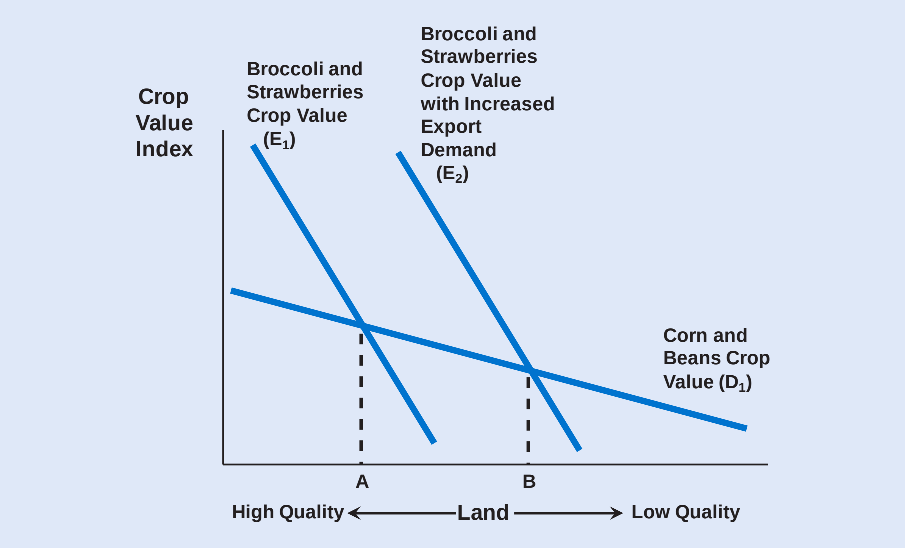
In the figure, land is rated by quality on the *x*-axis, with the highest quality land on the left side, and quality declining as we move rightward. The *y*-axis shows the value of crops grown on the land. This **crop value index** will differ depending on how the land is used. Some crops require higher-quality land and produce higher value per acre. Other crops grow on land of varying quality but produce less market value per acre. In economic terms, the crop value index represents the **marginal revenue product** of the land, which is the **marginal physical product** (additional quantity of a particular crop) multiplied by the price of the crop.

crop value index an index indicating the relative value of production of different crops on a given quantity of land.

marginal revenue product the additional revenue obtained by increasing an input level by one unit; equal to marginal physical product multiplied by marginal revenue.

marginal physical product the additional quantity of output produced by increasing an input level by one unit.

Figure 16.10 Land Quality, Crop Value, and Land Use



For example, in Mexico much land is devoted to growing corn and beans for local consumption. But growing broccoli and strawberries for export produces higher revenues. The intersection of the two crop value lines D_1 and E_1 shows how the land will be divided between production for export and production for domestic use. On the high quality land to the left of point A, the most valuable product is the export crop, for which the land will be used. Corn and beans will be grown on the lower-quality land to the right of point A.

Now suppose that the demand for export crops increases, as shown by crop value line $E_{2,}$ while demand for domestic foods remains the same. The crop value line for exported products rises, reflecting higher prices for broccoli and strawberries. As a result, the land use pattern changes, with export production expanding up to point B and domestic production squeezed onto lower-quality land to the right of Point B. In Mexico, this land use trend has accelerated as a result of the North American Free Trade Agreement (NAFTA).[4]

What does this imply for the environment and for the nutritional status of the population? One likely result is that larger commercial farms will displace smaller farmers who lack good access to export markets. This will increase pressure on the marginal farmlands (to the right in the graph). Hill slopes, forest margins, and arid lands are all especially vulnerable to the kind of environmental degradation that results when displaced people move to whatever land is available. We see the effects of this throughout much of Africa, Latin America, and Asia.

If revenues from export crops are unequally distributed, poorer people's diets will worsen as less corn and beans are produced for domestic consumption. Small farmers who share in export revenues can buy imported foods with the proceeds from cash crops, but more frequently they will lose out to larger producers in export markets.

16.3 PROJECTIONS FOR THE FUTURE

Population projections for the first half of the twenty-first century, as discussed in Chapter 15, show total world population reaching a level of around 9–10 billion by 2060. What new stresses will the additional demand for food place on the environment?

Will we exceed agricultural **carrying capacity**? Will we experience food shortages?

> **carrying capacity** the level of population and consumption that can be sustained by the available natural resource base.

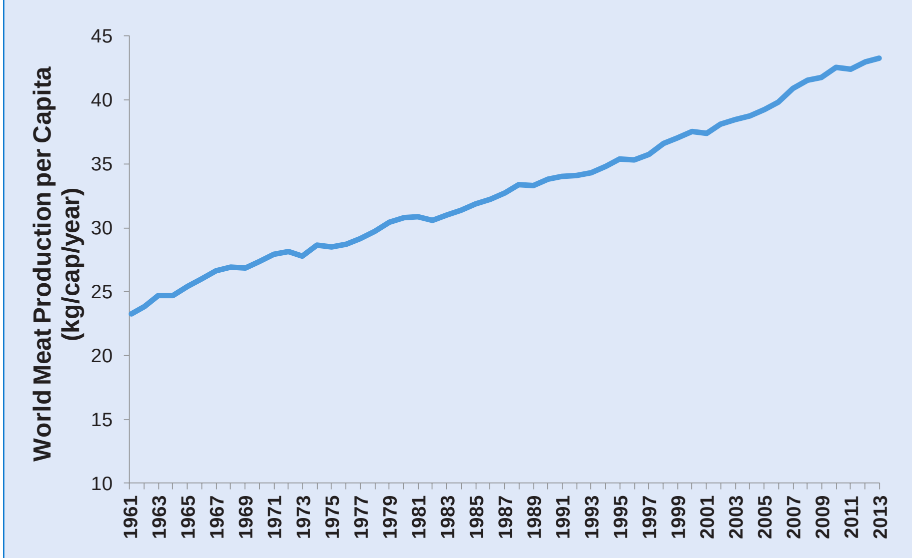
As of 2012–2014 the world produced about 2.7 billion metric tons of cereals (Figure 16.4). If evenly distributed, this would provide each person with about 385 kilograms (kg) of grain (cereals) per year—approximately 1.05 kg, or 2.3 pounds, per day. This grain crop requires about half the world's cropland. The other half is devoted to vegetables, fruits, oilseeds, root crops, and nonfood crops such as cotton.[5]

This level of food production would be adequate to provide each person with a mostly vegetarian diet, supplemented with a little meat, fish, or eggs—a diet characteristic of much of the developing world. The largely meat-centered diet characteristic of most of the developed world, however, requires much larger amounts of grain per person—not consumed directly, of course, but used for livestock feed. About three-quarters of the U.S. domestic consumption of cereal, for example, goes to feed cattle, pigs, and poultry.

Globally, therefore, distribution of the existing output is significantly unequal. Annual grain consumption in the United States is about 900 kg per capita, including direct consumption and feed grains for livestock. In the developing world, it averages under 300 kg per capita. Consumption levels throughout much of the developing world are sufficient for an adequate non–meat-centered diet, but inequality of distribution within countries leaves many of the poorest with inadequate levels of food consumption.

As economic development proceeds, per-capita demand for food rises. This is partly because poorer people can afford to buy more basic foods and partly because middle-class consumers shift to a meat-based diet, leading to growing meat consumption (see Figure 16.11). As we look ahead to the future, we must prepare to provide for both an increased total population, and a higher average consumption per person.

Figure 16.11 Global Meat Production per Capita (kg/cap/year), 1961–2013



Source: FAOSTAT, Food and Agriculture Organization of the United Nations, Statistics Division, http://faostat3.fao.org/.

Future Production and Yield Requirements

Following the 2007–2008 food price increases, many analysts rang alarm bells regarding our ability to feed the world in 2050. "With almost 80 million more people to feed each year, agriculture can't keep up with the escalating food demand. FAO estimates that we have to double food production by 2050 to feed an expected 9 billion people, knowing that one billion people are already going to bed hungry every day," warned the head of the Consultative Group on International Agricultural Research.[6]

More recent FAO estimates project a 60 percent increase of agricultural production from 2005 to 2050, not a doubling. This is still a major challenge. Meeting the challenge will require not only increasing agricultural production, but also improving people's access to food in their communities, and drastically reducing pre- and post-harvest food losses and waste, as well as increasing efficiency in the use of water and other natural resources.[7] Indeed, addressing food waste alone would save large quantities of food for human consumption. The FAO has estimated that roughly one-third of the food produced in the world for human consumption every year, approximately 1.3 billion tonnes (metric tons) gets lost or wasted. Food losses and waste amounts to roughly US$ 680 billion in industrialized countries and US$ 310 billion in developing countries.[8] Even assuming improved policies, it will be essential for agricultural yields to continue to grow at a rate consistent with historical trends (about 1.1 percent per year), in order to meet the projected demand in 2050.[9]

A number of factors could adversely impact projections for future yield increases. These include:

- Biofuels expansion: the FAO models assume that the lands dedicated to grow the crops used to produce biofuels would not expand beyond 2020, which is inconsistent with current growing demand for biofuels. (See Box 16.1.)
- Climate change: the FAO models did not incorporate the impacts of climate change on agricultural production at the horizon of 2050.
- Other negative impacts on yields arising from environmental degradation, overdraft of water supplies, and loss of soil fertility due to intensive agricultural production.

Impact of Climate Change on World Agriculture

As we saw in Chapters 12 and 13, potential impacts of climate change vary according to different global warming scenarios. The Intergovernmental Panel on Climate Change (IPCC) has specifically analyzed the potential impacts on food production systems.[10] Global warming is already affecting global agricultural patterns. While some high-latitude regions benefit from warmer temperatures, low-latitude regions are expected to experience increasing negative impacts, especially in Africa, Asia, and in Central and South America. Southern European countries will also be affected negatively by global warming. Impacts include:

- Increased inter-annual variability of crop yields, especially due to changes in precipitation.
- Increased spread of invasive weeds, pests, and crops diseases.
- For the major crops (wheat, rice, and maize) in most regions of the world, an increase in the average global temperature of more than approximately 2°C will have negative effects on yields.[11]
- Nutritional quality of food and fodder, including protein and micronutrients, will be negatively affected by elevated CO_2 concentrations.
- Global temperature increases of 4°C or more, combined with increasing food demand, would pose even more significant risks to food security globally and regionally.

Box 16.1
BIOFUELS AND FOOD SECURITY

The impact of biofuels on food availability is direct, as lands are diverted from food production to grow biofuel crops (typically corn or soy). By 2012, 40 percent of corn grown in the U.S. was used for ethanol production, compared to less than 10 percent in 2001 (as shown in Figure 16.7). The share of corn allocated to feeding livestock declined by more than one-third, as did the share of corn exports. Some models show that a doubling of demand for biofuels would have dramatic results, raising prices of basic crops, requiring an increase in cultivated land, and putting additional millions of people at risk of hunger. The rapid deployment of second generation biofuels, which are more efficient (in terms of amount of energy produced per hectare cultivated) could mitigate some of these negative impacts on food production. But even assuming more efficient production, increased demand for biofuels would increase prices significantly as fuel demand would compete with food demand for limited agricultural supply.

In addition to diverting land away from food production, the cultivation of crops like maize and soy to produce biofuels requires large water inputs (discussed further in Chapter 20). Given the problems of water scarcity in many regions of the world, which will likely worsen under the effect of climate change, increasing reliance on biofuels may pose serious threats to **water security** and **food security**.

Sources: Wise, 2013; United Nations University, 2013.

The IPCC projects that all aspects of food security will potentially be affected by climate change, including food access, utilization, and price stability. Changes in temperature and precipitation will contribute to increased global food prices by 2050, with models predicting increases ranging from 3 percent to 84 percent, depending on modeling assumptions.

Given the pressures of increasing food and biofuel demand, as well as the threats to agriculture posed by climate change, the critical question becomes the **environmental sustainability** of agricultural production. To assess the likelihood of an adequate solution to the food problem, we must consider in more detail the environmental stresses associated with pushing global agricultural systems to their limits.

food security a situation when all people have access to sufficient, safe, nutritious food to maintain a healthy and active life.

water security sustainable access to adequate quantities of acceptable quality water to sustain human well-being and socio-economic development.

environmental sustainability the continued existence of an ecosystem in a healthy state; ecosystems may change over time but do not significantly degrade.

nutrient recycling the ability of ecological systems to transform nutrients such as carbon, nitrogen, and phosphorus into different chemical forms.

16.4 AGRICULTURE'S IMPACT ON THE ENVIRONMENT

Soil Erosion and Degradation

With the exception of some hydroponics and aquaculture, almost all agriculture depends on soil. Soil, as we have noted, can be either a renewable or a depletable resource. Ideally, agricultural techniques should not degrade soils and should replenish soil productivity over time through **nutrient recycling** from crop residues. If this were the case, agricultural output would be truly sustainable and could continue at present levels indefinitely.

Unfortunately, the situation in almost all the world's major agricultural areas is quite different: Soil erosion and degradation is widespread. The term "land degradation" encompasses a wide variety of land conditions, such as desertification, salinization, waterlogging, compaction, contamination by pesticides, encroachment of invasive species, decline in the quality of soil structure, loss of fertility, and erosion by wind and water.[12]

All of these forms of degradation are severe problems, affecting lands all over the world. According to a 2011 FAO report, 33 percent of the earth's land was moderately to highly degraded, with a majority of this land in areas with high poverty rates.[13] An additional 5 to 7 million hectares of agricultural land are lost to soil degradation annually. Of all the causes of degradation, erosion is the most widespread:

> Soil erosion is a disastrous environmental problem throughout the world. Erosion is a slow insidious problem that is continuous. Indeed, 1 mm of soil, easily lost in one rain or wind storm, is so small that its loss goes unnoticed by the farmer and others. Yet this loss of soil over a hectare of cropland amounts to about 15 tons/ha. Replenishing this amount of soil under agricultural conditions requires approximately 20 years; meanwhile the lost soil is not available to support crops.[14]

Soil is being lost worldwide at 10 to 40 times the rate at which it can be replenished naturally. Soil loss rates are typically highest in developing countries; in Asia, Africa, and South America, soil erosion rates on cropland range between 20 and 40 tons per hectare per year.[15] Erosion damages crop productivity by reducing the availability of water, nutrients, soil organic matter, and soil biota. Water resources are also degraded by sediments and pollutants associated with erosion. In addition to soil loss from erosion, further soil degradation occurs from excessive irrigation, overgrazing, and destruction of trees and ground cover.

The Economics of Erosion and Erosion Control

In many cases, farmers can greatly reduce erosion and soil degradation by techniques such as **crop rotation and fallowing**—alternating grain and legume crops and taking the land out of production every few years. The farmer's costs include forgoing revenues in any year when the land is out of production and possibly settling for lower revenues in years when the land produces crops other than those with the highest value. Farmers must make an economic calculation as to whether the immediate costs of erosion control are worth the long-term benefits.

Consider a simple example. Suppose that a farmer can obtain \$100,000 in annual revenues by continually growing the highest-value crops with no provision for rebuilding soils or erosion control. Under these conditions, erosion will cause an annual decline of about 1 percent in yield. An effective erosion control program will reduce revenues by \$15,000 per year. Is the program worth it to the farmer?

The answer depends on the **discount rate** used to balance present versus future costs. One percent yield loss means a monetary loss of \$1,000. But this is not just a one-time loss; it will continue into the future. How do we evaluate this stream of losses resulting from one year's erosion? In economic terms, we apply a discount rate as discussed in Chapters 5 and 7. Suppose that we select a 10 percent discount rate. The **present value** (PV) of the stream of losses extending indefinitely into the future is equal to:

crop rotation and fallowing an agricultural system involving growing different crops on the same piece of land at different times and regularly taking part of the land out of production.

discount rate the annual rate at which future benefits or costs are discounted relative to current benefits or costs.

present value the current value of a stream of future costs or benefits; a discount rate is used to convert future costs or benefits to present values.

$$PV = (-\$1{,}000)(1/0.10) = -\$10{,}000.$$

The benefits of erosion control are thus $10,000—not enough, in this example, to justify $15,000 in lost revenue. Under these conditions, it is economically optimal to continue the erosive practices—but it is certainly not ecologically sustainable. Following this economic logic, the farmer will leave severely degraded land for the next generation.

Unfortunately, many farmers are under exactly this kind of economic pressure to maximize short-term revenues. Note that if we used a lower interest rate—say, 5 percent—the benefits of erosion control, calculated at $20,000, would exceed the costs and in theory make erosion control economically beneficial. Even so, the short-term losses might still be difficult to accept. An ecologically sound soil management policy is thus dependent on the farmer's foresight, relatively low interest rates, and the financial flexibility to invest in erosion control today for long-term benefits. Erosion control can be promoted by targeted government low-interest loan programs to support soil conservation measures.

Off-farm effects of erosion are an additional problem. In many areas, major dams have silted up with eroded soil, ultimately destroying their potential for power generation and wasting billions in investment. Heavy **siltation** can also cause extensive damage to stream and river ecology. Because these costs are **externalities** from the farmer's point of view, a social decision is required to respond to this aspect of erosion impacts.

siltation pollution of water caused by increased concentration of suspended sediments.

externalities effects of a market transaction that change the utility, positively or negatively, of those outside the transaction.

Environmental Effect of Fertilizer Use

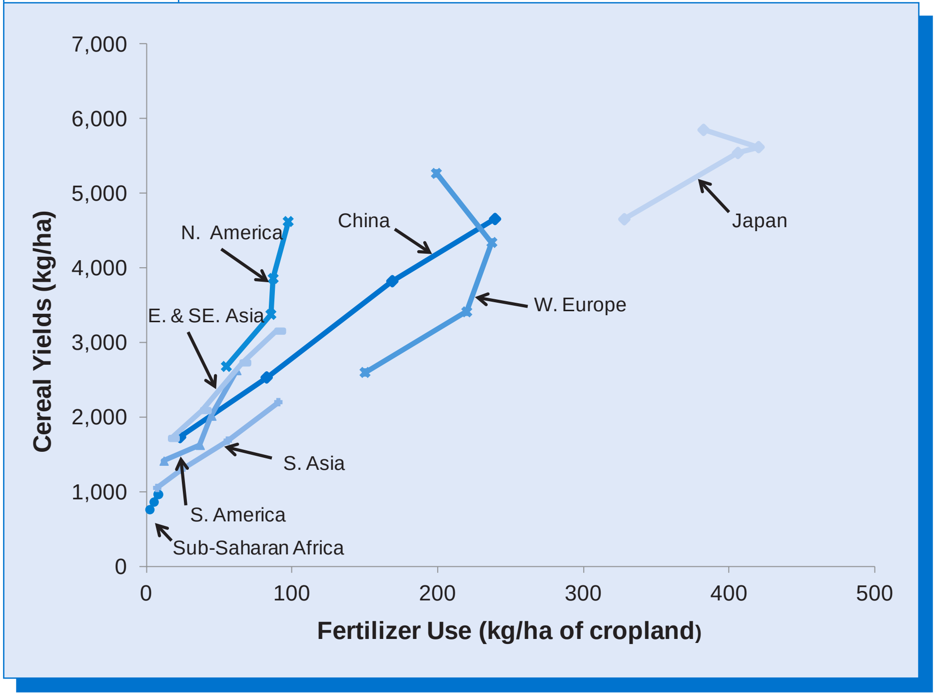
The steady increase in average yields characteristic of modern agriculture depends strongly on increased fertilizer use. Figure 16.12 shows this pattern for major world regions over a 40-year period from 1960 to 2000. Increased fertilizer use is clearly associated with higher yields. The lines for each region, followed from lower left to upper right, indicate trends. Over time, countries tend to shift from traditional agriculture with low fertilizer input to modern agriculture's heavy fertilizer use and high yields. All major regions except Africa have followed this trend, resulting in food output generally outpacing population growth over the long term. Africa has seen little increase in use of fertilizer and other agricultural inputs and concomitantly little increase in yields over the 40-year period.

What are the environmental implications of this "modernizing" process in agriculture? In general, intensive agricultural techniques rely on a "package" of inputs, including fertilizer, pesticides, irrigation, mechanization, and high-yielding crop varieties. In Figure 16.12, fertilizer per hectare serves as what economists call a **proxy variable** for this package. Higher use of fertilizer is so strongly associated with higher use of the other inputs that measuring fertilizer use alone gives us a good idea of the degree of agricultural intensity. Each of these inputs, however, relates to specific environmental problems, and as high-yield input use has increased, so has the seriousness of these environmental problems.

proxy variable a variable that is meant to represent a broader concept, such as the use of fertilizer application rates to represent the input-intensity of agricultural production.

Fertilizer supplies nutrients to the soil and therefore to crops. Most fertilizers supply the three major nutrients of nitrate, phosphate, and potassium. But a significant portion of the nutrients applied do not reach the crops as intended. Instead, they leach into ground and surface water, where they become serious pollutants.

Figure 16.12 Yield/Fertilizer Relationship for Major Regions: Averaged Data for Periods 1961–1970, 1971–1980, 1981–1990, and 1991–2001



Source: FAOSTAT, Food and Agriculture Organization of the United Nations, Statistics Division, http://faostat3.fao.org/. (Some fertilizer series have been discontinued.)

Excessive nitrate in water is damaging to human health. Nitrates and phosphates also causes the **eutrophication** of rivers, lakes, and even oceans, by fostering the growth of unwanted algae that chokes out other life. Most agricultural areas in the U.S. Midwest and West suffer from these problems. In the Gulf of Mexico, a huge "dead zone" caused by agricultural runoff covers an area that reached a record-breaking size of 8,000 square miles (more than 20,000 square kilometers) in the summer of 2013, threatening commercial and recreational fisheries.[16] In the Mediterranean, large portions of the sea have suffered severe ecological damage from agricultural runoff pollution, with giant mats of algae blanketing coastlines in the Aegean Sea and elsewhere. Inefficient and excessive fertilizer use has created especially severe agricultural problems in Russia and Eastern Europe. Inland seas such as the Black and Caspian Seas have experienced extinctions of numerous local species as a result.

eutrophication excessive growth of oxygen-depleting plant and algal life in rivers, lakes, and oceans

micronutrients nutrients present in low concentrations in soil, required for plant growth or health.

Another damaging effect of excessive fertilizer use is more subtle. As large amounts of nitrate, phosphate, and potassium are added to the soil year after year, other nutrients present in smaller quantities—called **micronutrients**—become depleted. Micronutrients include boron, copper, cobalt, and molybdenum. While some of these substances can be damaging in large amounts, trace amounts are important for plant growth and human nutrition. Depletion of soil nutrients occurs when nutrient removal by crops exceeds nutrient additions through manures and fertilizers. This gradually reduces both yields and nutritional values of the crops. Like erosion, these are long-term effects, giving farmers little incentive to respond to them so long as current yields are high. The problem is widespread in areas practicing intensive agriculture. For example, large parts of India, such as Punjab, Haryana, Uttar Pradesh and Bihar, which produce 50 percent of India's grains and feed about 40 percent of India's population, are experiencing multiple nutrient deficiencies in their soils.[17]

Fertilizer production is also energy intensive. In effect, modern agriculture replaces solar energy and human labor with energy extracted from fossil fuels.[18] Agricultural energy consumption thus contributes to the environmental problems associated with fossil-fuel energy consumption discussed in Chapters 11–13, including climate change. In terms of greenhouse gas emissions, the agriculture sector contributes not only CO_2 emissions, but also methane and nitrous oxide emissions. The sector of agriculture, forestry and other land use represented 24 percent of global greenhouse gas emissions in 2010—those emissions mostly being produced by the cultivation of crops and by livestock.[19]

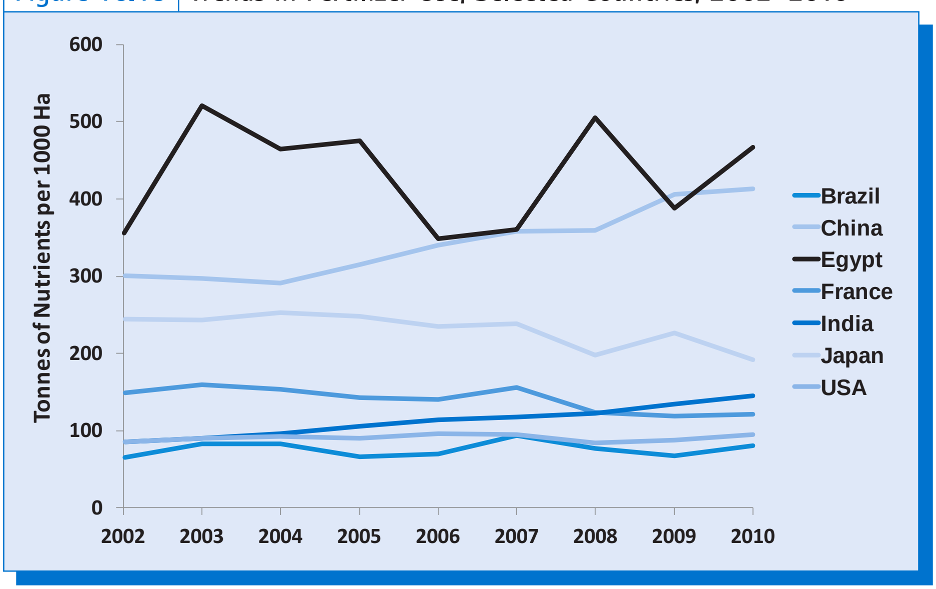
Agriculture generally accounts for only about 2–5 percent of total national energy use, although the percentage can be higher for regions with large agricultural sectors such as California (6−8 percent).[20] Although not the major component of energy-related issues, this percentage is not insignificant, particularly for developing countries with growing populations that must buy imported energy.[21]

Artificial nitrogen applied to crops now exceeds the amount supplied through natural nitrogen fixation by soil microorganisms. As noted in Chapter 9, human intervention in the earth's **nitrogen cycle** has already exceeded safe planetary boundaries (Figure 9.3). According to one recent study, global human additions to the nitrogen cycle are 1.5 tonnes N/km^2/year, three times the high risk limit. In the United States, the level averages 4.1 tonnes N/km^2/year, seven times the limit, and in some of the most intensive agricultural areas, such as the San Joaquin Valley in California, the level reaches 10.1 tonnes N/km^2/year, 18 times the limit, causing severe air pollution and contamination of water resources, both with serious health consequences.[22]

nitrogen cycle the conversion of nitrogen into different forms in the ecosystem, including the fixation of nitrogen by symbiotic bacteria in certain plants such as legumes.

Furthermore, the use of fertilizer is projected to increase steadily to provide the yields needed for the twenty-first century, especially

Figure 16.13 Trends in Fertilizer Use, Selected Countries, 2002–2010



Source: FAOSTAT, Food and Agriculture Organization of the United Nations, Statistics Division, http://faostat3.fao.org/.

in the developing world. Perhaps the most encouraging trends in Figure 16.12 are the reductions in fertilizer use seen in recent years in Western Europe and Japan, implying more efficient use since at the same time yields have continued to increase. If this pattern could be duplicated more widely, agricultural productivity could increase at lower environmental cost. As shown in Figure 16.13, between 2002 and 2010 fertilizer use declined in some countries but increased in others, reaching very high levels, for example, in Egypt and China.

Pesticide Use

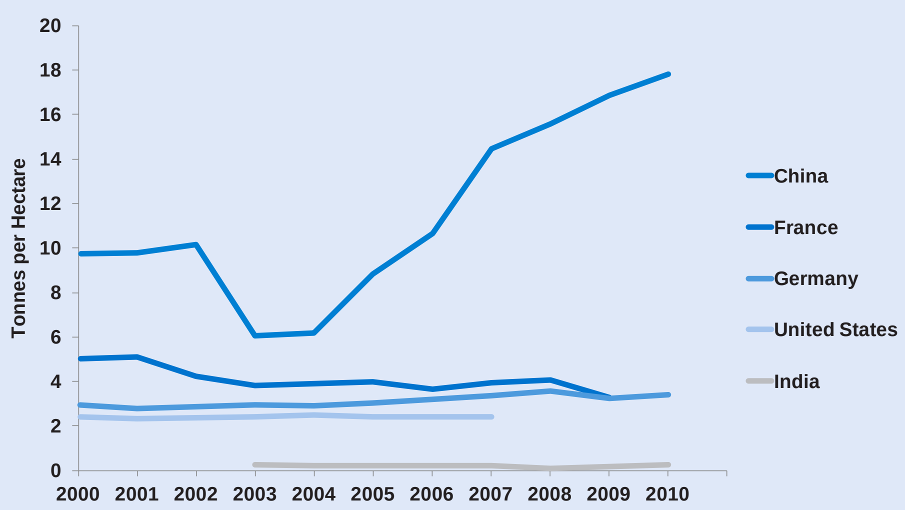
Like fertilizer use, pesticide use has risen rapidly with the spread of modern agriculture. Pesticide use in the United States has leveled off after approximately doubling between the 1960s and 1980s, but in many developing countries pesticide use is still rising (see Figure 16.14).

Numerous health and environmental problems have accompanied this increase. Pesticides may affect agricultural workers directly—pesticide poisoning is a serious and widespread problem throughout much of the developing world.[23] Residues in food affect consumers: measurable levels of chlorinated pesticides can be found in breast milk, and the cumulative impact of many pesticides on the human body is a serious concern. The carcinogenic effects of many pesticides are well known, and a more recent focus of research has seen effects on reproductive systems.[24]

Pesticides also affect ecosystems in various ways. Groundwater pollution from pesticides is a common problem in agricultural areas (see Box 16.2). Unintended extermination of beneficial species can lead to pest outbreaks far worse than the original problem. Since World War II (when the chemistry for many pesticides emerged), rapidly expanding pesticide use has paralleled an equally rapid expansion in **resistant pest species** (Figure 16.15). Similarly, excessive use of antibiotics in animal feed has encouraged the development of antibiotic-resistant microbes.

resistant pest species pest species which evolve resistance to pesticides, requiring either higher pesticide application rates or new pesticides to control the species.

Figure 16.14 Pesticides per Hectare in Selected Countries, 2002–2013



Source: FAOSTAT, Food and Agriculture Organization of the United Nations, Statistics Division, http://faostat3.fao.org/.

Box 16.2
CONTROLLING AGRICULTURAL POLLUTION

Agricultural pollution from erosion, fertilizers, and pesticides is often a more difficult policy problem than pollution from well-defined industrial sources. Runoff from agriculture is called **nonpoint-source pollution**, meaning that it originates from a wide area, affecting water supplies and downstream communities. In addition, factory farms pose a huge problem of animal waste released into water supplies. According to the Environmental Protection Agency, hog, chicken, and cattle waste has polluted 35,000 miles of rivers in 22 states and contaminated groundwater in 17 states. In the U.S., natural nitrogen and phosphorus cycles are being seriously imbalanced by fertilizers, 80 percent of which is attributable to meat production. Factory farms, also known as Concentrated Animal Feeding Operations (CAFOs), are one of the largest consumers of water in the U.S. Pollution from livestock in CAFOs is associated with many types of waterborne disease, as well as problems like bacterial outbreaks, red tides, and algae blooms; and, along with other agricultural pollution, contributes to the dead zone in the Gulf of Mexico.

Reducing nonpoint source pollution requires altering production methods in agriculture. The use of fertilizers, pesticides, and intensive farming methods can bring benefits in terms of reduced prices to consumers. But while these benefits are automatically internalized into market mechanisms—farmers who can produce at lower cost will gain greater market share—external costs are not considered. Thus government policies must be oriented toward making sure that agricultural input and output prices reflect true social costs and benefits.

This implies reducing subsidies for agricultural inputs, as well as subsidies directed at increasing production. Support for research and promotion of alternative, lower-polluting techniques can be justified on the grounds of internalizing positive externalities. Strict regulation of factory farming and incentives for non-factory livestock production may raise prices to consumers—but lower prices cannot be justified on economic grounds if they fail to reflect full social costs.

Particularly in the developing world, where the use of pesticides is steadily rising, information and support for production methods with lower pesticide use requires government commitment and investment. In the 1980s Indonesia invested as much as $1 million per year in research and training in ecologically oriented pest control, following a destructive infestation of the brown planthopper, which had spiraled out of control when excessive pesticide use eliminated its natural predators. The Indonesian program has been a success—crop yields increased by 12 percent with lower environmental impacts—but replication of such programs depends on initial investments, often hard to come by in developing nations.

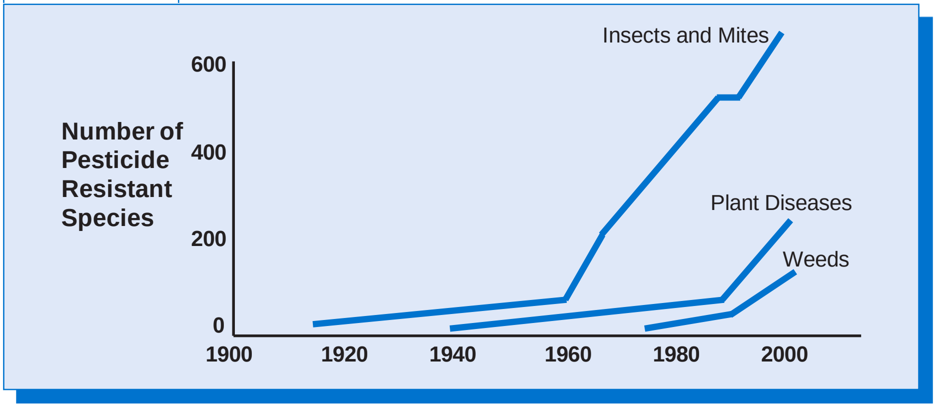
Sources: Karlsson, 2004; U.S. Environmental Protection Agency, "Animal Feeding Operations," www.epa.gov/agriculture/anafoidx.html; Wilson and Tisdell, 2001; Obenchain and Spark, 2015.

These developments are no surprise to ecologists, who understand the dangers of upsetting a natural species balance. However, such consequences are difficult to quantify in monetary terms or to introduce into farm-level decision-making. In addition, vested interests—the manufacturers of agricultural chemicals—continually seek to promote the expanded use of pesticides.

Information asymmetry—a situation in which participants in a market economy have different levels of access to information—is characteristic of pesticide regulation. In the case of agricultural technologies, consumers of food products,

> **information asymmetry** a situation in which different agents in a market have different knowledge or access to information.

Figure 16.15 Increase in Pesticide-Resistant Species in the Twentieth Century



Source: Adapted from Gardner, 1996.

Box 16.3

GENETICALLY MODIFIED FOODS—A CONTROVERSIAL TECHNOLOGY

Over 175 million acres in the United States were cultivated with genetically modified (GM) crops in 2015: 89 percent of corn acreage, 94 percent of soybean, and 89 percent of cotton acreage. Worldwide, 444 million acres were planted with GM crops, with the U.S., Brazil, Argentina, India, Canada, and China having the largest areas in GM crops. Total global GM acreage declined slightly in 2015, after having increased rapidly for the previous two decades.

Although proponents list a variety of potential benefits from GM crops, opponents argue that the widespread use of GM products creates health and environmental hazards. Opposition to the introduction of genetically modified organisms and the incorporation of genetically modified ingredients into regular consumer products first started and is still strong in the European Union but now seems to be a worldwide concern, with a number of countries placing or considering restriction on GM foods.

According to proponents, high-yielding GM crops could replace lower-yielding crops in developing countries, and engineering of vitamins into crops such as rice could provide a more nutritious diet for low-income consumers. Increasing the productivity of crops would mean that farmers would need to bring less marginal lands into cultivation, and help provide for the increasing demands of a growing global population. New crop varieties could mean more efficient weed and insect control, and increase the potential for disease-resistance and crops that can grow on arid, degraded, or saline lands.

Opponents of GM foods challenge these claims. They argue that GM foods have proved not to increase yields, and also point to ecological damage and possible health effects. GM plants can crossbreed with natural varieties to produce strains that could escape into the natural environment, a phenomenon known as “gene flow.” GM corn could endanger native corn varieties in Mexico, and the U.S. Forest Service has warned that genetically engineered grass could adversely impact national forests and grasslands. Widespread use of pesticide-producing plants, and of pesticide-resistant crops in conjunction with expanded commercial pesticide use, can promote the emergence of resistant pests.

Health effects are more controversial. Some studies indicate toxic and allergenic effects of GM foods on laboratory and farm animals. A recent report and even government regulators, may be unaware of the nature and dangers of pesticide residues. Pesticide producers generally know the most about the chemical composition and potential effects of pesticides. Because thousands of different compounds are on the market, mastering this information—even if it is available—is practically impossible for farmers and consumers. Government regulators have trouble keeping up with the rapid rate of introduction of new compounds and usually must narrow their focus to, for example, extreme carcinogenicity, possibly failing to detect reproductive and other problems.

In such circumstances it is unlikely that the **external costs** of pesticide use will be fully understood and internalized. Regulatory issues have become even more complex with the introduction of genetically modified crops, often by the same chemical companies that are major producers of agricultural pesticides (see Box 16.3).

nonpoint-source pollution pollution that is difficult to identify as originating from a particular source, such as groundwater contamination from agricultural chemicals used over a wide area.

external cost(s) a cost, not necessarily monetary, that is not reflected in a market transaction.

by the National Academy of Sciences, on the other hand, found that genetically-engineered crops were generally safe to eat. But the academy also found that GM crops didn't increase crop yields, and did lead to widespread and expensive problems with herbicide-resistant weeds.

Issues of Corporate Control

Multinational corporations dominate the global market for GM seeds. Such a market places small-scale farmers and developing countries at a disadvantage, since they must purchase seeds and accompanying products such as pesticides, rather than maintaining control over their own seeds and production techniques.

Ecological and health effects are also a significant issue. Widespread use of herbicide-tolerant crops in combination with the herbicide glyphosate has led to almost a tenfold increase in glyphosate use. This has resulted in a rapid decline in monarch butterfly populations due to loss of their milkweed food source, as well as the spread of weeds immune to glyphosate. Glyphosate has also recently been identified as a "probable" carcinogen by the World Health Organization (WHO).

The staunch anti-GM foods stance taken by some countries is causing trade conflicts between GM food producers in the United States and importing countries. European governments, some Asian and African governments, and U.S. activists are calling for the labeling of foods that contain GM ingredients and the right to exclude GM products from their markets. Some farmers and industry lobbyists, mainly in the United States, contend that this will result in higher prices because GM and non-GM foods will have to be grown, transported, stored, and processed separately, and that labeling will stigmatize the products.

GM labeling has taken a limited step forward in the U.S. After a mandatory GM food labeling law was passed by the state of Vermont, a less stringent national law that pre-empts the Vermont law was passed in 2016. The law requires an indirect form of labeling, mandating that food packages present Quick Response Codes or electronic links to scan for information on food content, with actual labeling being optional.

The debate on GM foods is likely to continue, with significant implications for agriculture and for international trade (discussed further in Chapter 21).

Sources: U.S. Department of Agriculture, 2012; Andrew Pollack, "Acreage for Genetically Modified Crops Declined in 2015," *New York Times*, April 13, 2016, and "Genes from Engineered Grass Spread for Miles," *New York Times*, September 21, 2004; Danny Hakim, "Doubts about the Promised Bounty of Genetically Modified Crops," *New York Times*, October 29, 2016; Vargas-Parada, 2014; National Academy of Sciences, 2016; Center for Food Safety, 2015; Newton, 2014, p. 88–94; Cressey, 2015; U.S. Geological Survey, 2014.

Irrigation and Water Resources

The spread of irrigation has been just as important as increased fertilizer use in expanding agricultural output. Irrigation greatly improves yields and often permits **multiple cropping** in areas dependent on seasonal rains. The most optimistic projections of further yield increases in developing-country agriculture rely heavily on expanded irrigation. But, as with fertilizer and pesticides, the short-term benefits of irrigation are often linked to long-term environmental damage.

multiple cropping an agricultural system involving growing more than one crop on a piece of land in the same year.

salinization and alkalinization of soils the buildup of salt or alkali concentrations in soil from the evaporation of water depositing dissolved salts, with the effect of reducing the productivity of the soil.

common property resources resources that are not subject to private ownership and are available to all, such as the oceans or atmosphere.

Poor drainage causes irrigation water to build up underground, eventually causing fields to be waterlogged. In tropical areas, water that reaches the surface evaporates rapidly, leaving behind a buildup of dissolved salts and leading to **salinization and alkalinization of soils**. In the Indian state of Punjab, for example, millions of hectares of land have been damaged by salinization. Irrigation also increases fertilizer and pesticide runoff, polluting local surface and groundwater.

The farmland most dependent on irrigation often lies in precisely those arid regions where water is in short supply. This leads to overdraft of groundwater—pumping out underground reservoirs faster than the natural water cycle can refill them—a classic example of the **common property resource** problem discussed in Chapter 4. No individual farmer has an incentive to limit water use. As a result, currently productive agricultural regions face a waterless future after the aquifers are exhausted.

The Ogallala aquifer, which supports much of the irrigated agriculture of the western United States, is as much as 50 percent depleted in some areas, and its level continues to fall. Rapid declines in groundwater levels are also taking place in India, North China, and Central Asia (discussed further in Chapter 20).[25]

Withdrawals from rivers in arid areas can be equally damaging. Agricultural water demand has led to serious salinization problems in the Colorado River in the western United States as well as an international dispute over the increased salinity of the river water crossing the border into Mexico. Perhaps the worst case of excessive irrigation demand is the Aral Sea in the former Soviet Union; this inland sea lost 88 percent of its surface area and 92 percent of its water volume between 1960 and 2009 as a result of water withdrawals (primarily for cotton production) from the rivers that feed it. (In recent years, efforts by the World Bank and the government of Kazakhstan have led to a slow partial recovery, but large parts of the sea have been lost forever.)[26]

Limits on water supplies may be the most significant constraint on future agricultural expansion in large areas of the world. Irrigation accounts for 70 percent of total water withdrawal worldwide and more than 80 percent in developing countries (see Chapter 20). Most of China and the Indian subcontinent are close to the limits of their available water supply, and urban/industrial water demand is rising steadily. Much of Africa is arid or semiarid, as are large areas in West and Central Asia and in the western United States. Climate change, as noted above, is likely to intensify problems of water availability, as precipitation patterns change and mountain snowpack is lost. Given the clear economic incentives to expand irrigation, both the externality and the common property resource problems associated with water use mean that this expansion is likely to intensify resource and environmental problems.

16.5 SUSTAINABLE AGRICULTURE FOR THE FUTURE

All the problems discussed above are related to the spread of high-input industrial agricultural techniques. Some of the problems can be mitigated through increased efficiency—reducing fertilizer, water, and pesticide use while increasing output. But there are alternative approaches to agricultural production, which suggest a more dramatic change in agricultural production systems. Ecological analysis offers us a somewhat different understanding of the relationship between agriculture and the environment. Rather than seeing agricultural production as a process of combining inputs (including land, water, fertilizer, and pesticides) to maximize output, the analysis known as **agroecology** suggests that agriculture has to be understood as a process of intervention in the natural **biophysical cycles** responsible for plant growth.[27] These include the carbon cycle, nitrogen cycle, water cycle, and similar cycles for other plant nutrients.

In a natural state, solar energy drives these cycles. Traditional agriculture departs little from these natural cycles. Modernized agriculture relies on extra inputs of energy, water, nitrogen, and synthetic chemicals. This gives higher yields, but creates imbalances in all the natural cyclical processes. From this perspective, soil degradation, fertilizer and pesticide pollution, and water overdraft are results of disrupting natural cycles. To use another ecological concept, modern agriculture expands carrying capacity but does so at the cost of increasing ecological stresses.

Both the economic and the ecological perspectives can influence our definition of **sustainable agriculture**. A sustainable agricultural system should produce a stable level of output without degrading the environmental systems that support it. In economic terms, this means no significant un-internalized externalities, user costs, or excessive use of common property resources. From an ecological point of view, a sustainable system minimizes disruption to natural cycles and promotes long-term soil fertility and ecological balance.Production techniques such as organic fertilization by recycling of plant and animal waste, crop rotation, and **intercropping** of grains and legumes can maintain the soil's nutrient balance and minimize the need for artificial fertilizer. The use of reduced tillage, terracing, fallowing, and **agroforestry** (planting trees in and around fields) all help to reduce erosion. **Integrated pest management (IPM)** uses natural pest controls such as predator species, crop rotation, and labor-intensive early pest removal to minimize the use of chemical pesticides.

Efficient irrigation techniques and the use of drought- and salt-tolerant crop varieties can reduce water use. **Species diversity** can be promoted by multiple cropping (planting several different crops in the same field), rather than the **monoculture** (extensive planting of a single crop) pattern typical of modernized agriculture. Agroecological techniques can

agroecology the application of ecological concepts to the design and management of sustainable food systems.

biophysical cycles the circular flow of organic and inorganic materials in ecosystems.

sustainable agriculture systems of agricultural production that do not deplete the productivity of the land or environmental quality, including such techniques as integrated pest management, organic techniques, and multiple cropping.

intercropping an agricultural system involving growing two or more crops together on a piece of land at the same time.

agroforestry growing both tree and food crops on the same piece of land.

integrated pest management (IPM) the use of methods such as natural predators, crop rotations, and pest removal to reduce pesticide application rates.

species diversity or biodiversity the maintenance of many different interrelated species in an ecological community.

monoculture an agricultural system involving the growing of the same crop exclusively on a piece of land year after year.

also promote carbon storage in soils, helping to mitigate climate change. It is estimated that soils have been depleted of 50 to 70 percent of their natural carbon in the last century. As noted in Chapter 13, proper soil management could lead to reabsorption of up to 80 to 100 billion metric tons of carbon per year.[28]

Many of these techniques are already practiced by small-scale farmers working on small plots of lands, often with traditional farming techniques.[29] The UN Food and Agriculture Organization (FAO) has emphasized the potential of agroecology both for achieving sustainable food systems and also for responding to climate change and water shortages. According to the FAO:

> It is not an exaggeration to say that the sustainable food system of the future, considered as a whole, will represent a paradigm shift. Like traditional and indigenous agroecosystems, it will conserve resources and minimize exogenous inputs. Like industrial agriculture, it will be very productive. And unlike any system of food production that has heretofore existed on the planet, it will combine these attributes while distributing its benefits equitably among human beings and societies and refraining from displacing its costs onto natural ecosystems increasingly pushed to the brink of collapse.[30]

The widespread development of agroecological systems requires expanded access to information. Alternative techniques tend to be both **labor-intensive** and **information-intensive**. In developed countries, only a minority of farmers are sufficiently knowledgeable about the complex techniques of organic and low-input (minimum chemical use) agriculture to be able to make them pay. It is much easier to read the instructions on a bag of fertilizer or a canister of pesticide. In developing countries, traditional low-input farming systems have often been displaced by modernized "Green Revolution" techniques promoted by governments and international agencies. It is important to alter policies so as to support local farmers who often maintain both the knowledge and the crop varieties necessary for a sound agroecology.

labor-intensive techniques production techniques that rely heavily on labor input.

information-intensive techniques production techniques that require specialized knowledge; usually these techniques substitute knowledge for energy, produced capital, or material inputs, often reducing environmental impacts.

Farming systems can be considered sustainable without being completely organic, but many agroecologists favor organic systems—as, increasingly, do many consumers. In recent years, organic agriculture has expanded rapidly, but it still represents a small portion of total agricultural production (see Box 16.4). Government policies, such as the establishment of organic standards and reform of agricultural subsidy policies, will have an important influence on the future of organic farming.

Policies for Sustainable Agriculture

Without strong economic incentives to alter production methods, combined with widespread information and support for alternative techniques, most farmers will stay with established methods. A shift to more sustainable agriculture will require a combination of government policy and market incentives.

Important market incentives include the prices of fertilizer, pesticides, irrigation water, and energy. Many governments have policies that directly or indirectly subsidize these prices. According to a well-established principle of agricultural economics, price ratios for agricultural inputs determine the course of **induced innovation** in agriculture.[31] If fertilizer is cheap relative to land

induced innovation innovation in a particular industry resulting from changes in the relative prices of inputs.

Box 16.4
ORGANIC AGRICULTURE ON THE RISE

Organic production, which earned about $39 billion in the United States and $80 billion worldwide in 2014, is the most rapidly growing sector of agriculture. Organic agriculture is practiced in 172 countries, with approximately 2.3 million farmers growing organic crops on 43.7 million hectares of agricultural land. In the United States, there were more than 21,700 certified organic operations in 2014, representing a nearly 300 percent increase since 2002. According to a 2003 report by the Organization for Economic Cooperation and Development (OECD), organic agriculture constituted only 2–3 percent of production within the OECD (essentially the world's higher-income countries), but its share has grown rapidly since then in most OECD countries. The growth in organics is in response to the demand of consumers, who are often prepared to pay a premium for foods grown without pesticides or genetic modification. The advantages of organic foods are perceived to include health and environmental benefits, improved food quality and taste, accessibility of fresh produce, and assistance to small-scale local producers.

While yields tend to be lower and labor costs higher on organic farms, profitability is also higher as a result of price premiums and, in some cases, government support payments. Market-based policy approaches to promote organic agriculture include certification and labeling schemes, now adopted by almost all OECD countries. The European Union has a single, "harmonized" standard for organic agriculture, and the United States has put federal organic standards in place. Compliance with these standards helps exporters to expand organic production, but the variety of different standards can sometimes be confusing.

Some European governments have undertaken promotional campaigns to encourage the consumption of organic products. A few countries require the purchase of organic food by public institutions such as schools and hospitals. Many governments provide direct financial support to organic farmers, justifying this subsidy as a return for providing external benefits of environmental protection—for example, reducing nitrate, phosphate, and pesticide flows into water supplies. A small percentage of public agricultural research is also devoted to organic systems.

The OECD report concluded that conventional agriculture still retains an advantage due to government production subsidies and failure to address the problems of negative externalities associated with conventional systems. "Such policies provide incentives to adopt farming practices that increase production rather than those, like organics, which stress quality. . . . Governments need to address the externalities in conventional agriculture to provide a better use of resources and a more level playing field for organic systems." Recent research also suggests that the yield gap between organic and conventional agriculture is less than has commonly been assumed, and that "through appropriate investment in agroecological research, the yield gap could be reduced or even eliminated for some crops or regions."

Sources: Organization for Economic Cooperation and Development, *Organic Agriculture: Sustainability, Markets, and Policies* (Wallingford, UK: CABI, 2003); OECD Environmental Database, 2013; Matthew Saltmarsh, "Strong Sales of Organic Foods Attract Investors," *New York Times*, May 23, 2011; *The World of Organic Agriculture 2016*, *http://www.organic-world.net/yearbook/yearbook-2016.html*; U.S. Dept. of Agriculture, *http://www.usda.gov/wps/portal/usda/usdahome?contentid=usda-results-organic-agriculture.html*; Berkeley News, "Can Organic Crops Compete with Industrial Agriculture?" http://news.berkeley.edu/2014/12/09/organic-conventional-farming-yield-gap/.

and labor, the farm sector will develop and implement fertilizer-intensive methods. By providing low-cost fertilizer, farm chemicals, and water for irrigation, governments promote agricultural productivity—but at an environmental cost.

Policies to subsidize energy also promote the trend to more highly mechanized and input-dependent agriculture. Changing these policies would support the development of a more labor- and information-intensive agriculture with less environmental impact. In developing countries with large pools of unemployed and underemployed labor, promotion of labor-intensive agricultural development might have considerable employment as well as environmental benefits.

Removing energy and input subsidies would send a price signal to farmers to use less input-intensive techniques. Before they can respond effectively to these price incentives, however, farmers need information on alternative techniques—otherwise higher input prices will simply make food more expensive. Developing countries can combine valuable knowledge of traditional agricultural techniques with modern innovations, provided that energy-intensive monoculture does not sweep away traditional knowledge.

Agricultural subsidies in developed countries have been estimated at $200–$300 billion, but subsidies in the OECD have significantly decreased in recent years, from around $252 billion in 2013 to $212 billion in 2015.[32] Subsidies in OECD countries represented around 37 percent of farmers' income on average in the 1980s, whereas they only represented 17 percent in 2015. However, even with this approximate halving of subsidies in OECD countries, government support is still significant both in developed countries and in emerging economies, as seen in Table 16.1.

Most of these subsidies are environmentally destructive, promoting increased input and energy use. While developed countries typically promote production, resulting in agricultural surpluses, developing countries often reduce incentives for agricultural production by policies that lower prices paid to farmers. The goal is to provide cheap food for consumers, but the effect is to discourage local production. Widespread use of these counterproductive economic policies in agriculture leaves much scope for policy reforms that could benefit both food supply and the environment. Damaging subsidies could be removed or shifted to favor environmentally sound techniques and agricultural research. Better prices and improved credit systems for farmers can encourage both increased production and investment in soil conservation.

An example of an environmentally positive agricultural subsidy is the U.S. Conservation Reserve Program. Started in 1985, this program now covers 30 million acres of former cropland. Farmers receive payments to remove environmentally sensitive land from production, reducing erosion, protecting wetlands and water supplies,

Table 16.1 Subsidies (as Percent of Farmers' Income), Selected OECD Countries and Emerging Economies

	1986–88	1995–96	2013–2015
USA	21.2	11.9	8.8
European Union	39.0	33.8	19.0
Japan	64.0	58.0	48.2
Total OECD	37.0	29.7	17.6
Non OECD:			
Brazil	-	-	3.1
Russia	-	17.7	14.6
China	-	2.5	20.1

Source: OECD, 2016. *Agricultural Policy Monitoring and Evaluation*, Statistical Annex.

and providing habitat for wildlife, including endangered species. This program internalizes positive externalities, helps to preserve family farms, and provides greater land-use options for the future.[33]

On the demand side, it is clear that population size is a major determinant of food demand and indirectly of agricultural pressures on the environment. The ecological concept of carrying capacity, discussed in Chapters 9 and 15, implies a maximum population that the planet's resources can sustainably support. Our discussion of agricultural futures suggests that we are close to reaching that capacity and may have exceeded it if we consider long-term issues of soil erosion, water overdraft, and climate change. Population policy is therefore a central element in limiting the impact of agricultural production on the environment.

The other major demand-side variable is diet. As we have seen, a meat-centered diet implies much higher land, water, and fertilizer requirements per capita than a mostly vegetarian diet. Using land resources to produce meat for export also increases environmental pressures in developing countries. Thus, reducing meat consumption in developed countries and slowing the trend toward meat-centered diets in newly industrializing countries are important components of long-term sustainability.

Abolishing input subsidies will increase the price of meat compared to more input-efficient foods, and health motivations may lead to reduced demand for meat in developed countries. To the extent that consumers shift their preferences toward more vegetables, including more organically grown produce, the incentives to producers to employ less environmentally damaging techniques will grow.

The environmental problems associated with agriculture are complex and cannot be solved by simple cost internalization policies—though these will help. It will take major changes in consumer behavior, production techniques, and government price and agricultural policies to move to a sustainable agricultural system. The urgency of these issues will grow as population increases and cumulative soil and water impacts increase. The high-input agriculture that has been so successful in increasing world output during recent decades will not meet the needs of the twenty-first century without significant changes to promote sustainability.

Summary

Food production has outpaced population since the 1960s, allowing for slowly rising global per capita consumption. However, food distribution is significantly unequal, with around 800 million people receiving inadequate nutrition. Most suitable agricultural land is already being farmed, leaving relatively little room for further expansion. Yields have increased and continue to rise, but greater productivity has been accompanied by greater environmental impact, including erosion, soil degradation, and fertilizer and pesticide runoff.

Rates of growth in agricultural output have slowed, and in recent years prices of basic foods have risen significantly. In some developing countries, especially in Africa, per capita consumption has grown slowly, stagnated, or declined. Inequitable access to food means that basic food crops can be displaced by luxury or export food crops, increasing pressure on the poor and on environmentally vulnerable marginal lands.

Projections of future demand show a 60 percent increase in global food demand in the developing world by 2050. Because little potential exists for land expansion, this demand will require dramatic increases in yields. The challenge is to achieve this in an environmentally sustainable manner. Existing environmental effects associated with agricultural production make this a formidable task.

Erosion causes declining soil fertility as well as significant off-farm damage. Farmers facing short-term financial pressures often find investment in long-term conservation difficult. Fertilizer use has led to extensive runoff pollution and excessive nitrate release, affecting both water supplies and the atmosphere. Pesticide application is associated with a steady increase in the number of resistant pest species as well as with other negative impacts on ecosystems. Poorly planned irrigation systems have led to water overdraft and pollution as well as soil damage.

Future policies must promote agricultural sustainability. Agroecological practices, such as crop rotation, intercropping, agroforestry, and integrated pest management, can reduce input requirements and environmental impacts while maintaining high yields. Efficient irrigation and land management techniques have great potential, but require appropriate economic incentives for farmers to adopt them. Removing energy and input subsidies and providing information on environmentally sound techniques must accompany more equitable and efficient distribution and consumption patterns.

Key Terms and Concepts

agroecology

agroforestry

biodiversity

biofuels

biophysical cycles

carrying capacity

common property resources

crop rotation and fallowing

crop value index

depletable resource

discount rate

elasticity of supply

environmental sustainability

external costs

externalities

induced innovation

information asymmetry

information-intensive techniques

integrated pest management

intercropping

labor-intensive techniques

marginal physical product

marginal revenue product

micronutrients

monoculture

multiple cropping

nitrogen cycle

nutrient recycling

nutritional deficit

present value

proxy variable

renewable resources

resistant pest species

salinization and alkalinization of soils

species diversity

sustainable agriculture

Discussion Questions

1. What evidence would you use to evaluate the proposition that the world is reaching its maximum carrying capacity in terms of food supply? Some analysts believe that the world's agricultural capacity is adequate for a population of 9–10 billion people. Are you comfortable with this assertion? What factors are most important in assessing whether it will be possible to meet the growing food demands of an expanding population?

2. Which environmental impacts of agriculture are most amenable to market solutions? Consider the on-farm and off-farm impacts of erosion, for example. What kinds of incentives are required to induce greater erosion control? How much can be done through private initiative and how much through government policy?

3. How can we define the concept of sustainable agriculture? Can high-input agriculture be sustainable? Is organic agriculture sustainable? In what respects is our current agricultural system *not* sustainable and what kinds of techniques and policies are appropriate to respond to problems of unsustainability? How would you evaluate the economic costs and benefits of such policies?

Notes

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13. FAO, 2011b.
14. Pimentel and Burgess, 2013.
15. Shiva, 2016; Zuazo and Pleguezuelo, 2009.
16. Gliessman, 2015, p. 10.
17. Bhushan, 2016.
18. See Cleveland, 1994; Martinez-Alier, 1993.
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Web Sites

1. **www.ers.usda.gov.** Web site for the Economic Research Service, a division of the U.S. Department of Agriculture with a mission to "inform and enhance public and private decision-making on economic and policy issues related to agriculture, food, natural resources, and rural development." Their web site provides links to a broad range of data and analysis on United States agricultural issues.

2. **www.fao.org.** Web site for the Food and Agricultural Organization of the United Nations, an organization "with a mandate to raise levels of nutrition and standards of living, to improve agricultural productivity, and to better the condition of rural populations." Their web site includes extensive data on agriculture and food issues around the world.

3. **www.ota.com.** Homepage for the Organic Trade Association, "a membership-based business association representing the organic industry in Canada, the United States, and Mexico." Their web site includes press releases and facts about the organic agriculture industry.

4. **www.oecd.org/agriculture.** Web site for the Agriculture and Fisheries division of the Organization for Economic Co-operation and Development. The site includes data, trade information, and discussions of environmental issues. Note that the OECD also maintains a webpage on biotechnology.

5. **www.isric.org.** Web site for the International Soil Resource Information Center, providing information on global soil degradation and agricultural productivity loss, and on measures to conserve and reclaim soil productivity.

CHAPTER

17

Nonrenewable Resources: Scarcity and Abundance

Chapter 17 Focus Questions

- Are we running out of nonrenewable resources?
- How will prices for metals, minerals, and other nonrenewable resources change over time?
- What are the environmental costs of mining for mineral resources?
- How do economic incentives affect recycling of nonrenewable resources?

17.1 THE SUPPLY OF NONRENEWABLE RESOURCES

The planet has a fixed quantity of **nonrenewable resources**, including metal and nonmetal minerals, coal, oil, and natural gas. We have extensive supplies of certain resources, such as iron; others, such as mercury or silver, are in relatively limited supply. The global economy is using up these resources—often at increasing rates. Is this cause for alarm?

nonrenewable resources resources that do not regenerate through ecological processes, at least on a human time scale, such as oil, coal, and mineral ores.

Limited, nonrenewable resources cannot, of course, last forever, but issues regarding their use are complex, involving changes in resource supply and demand as well as the waste and pollution generated in their consumption. In this chapter we examine the dynamics of nonrenewable resource use, with a focus on minerals. Issues of nonrenewable energy resources, such as coal, oil, and natural gas, were addressed in Chapter 11.

Physical Supply and Economic Supply

In our initial analysis of nonrenewable resources in Chapter 5, we considered the allocation of a mineral resource over two periods. We assumed that both the resource quantity and quality were fixed. The economic principles derived from this simple example, including the analysis of **user costs** for resource pricing, are important, but a more sophisticated analysis must deal with real-world conditions. We usually see many different resource qualities (e.g., different grades of copper ore), and we rarely know with complete certainty the location and total quantity of resource deposits.

user costs opportunity costs associated with the loss of future potential uses of a resource, resulting from consumption of the resource in the present.

The **economic reserves** of a nonrenewable resource differ from its **physical reserves**. The physical supply (in the earth's crust) is the total amount available, which is finite but generally not precisely known. The economic reserves represent those known reserves that can be extracted profitably based on current prices and technology. Economic reserves provide the measure most commonly used in, for example, calculations of how long a nonrenewable resource might last under assumptions about prices, technology, and depletion rates, referred to as the **resource lifetime**. Economic reserves change over time for three main reasons:

- The resource is extracted and used over time, diminishing reserves.
- New resource deposits are discovered over time, increasing reserves.
- Changing price and technological conditions can make more (or less) of the known reserves economically viable. These factors make predictions of resource lifetimes an inexact science.

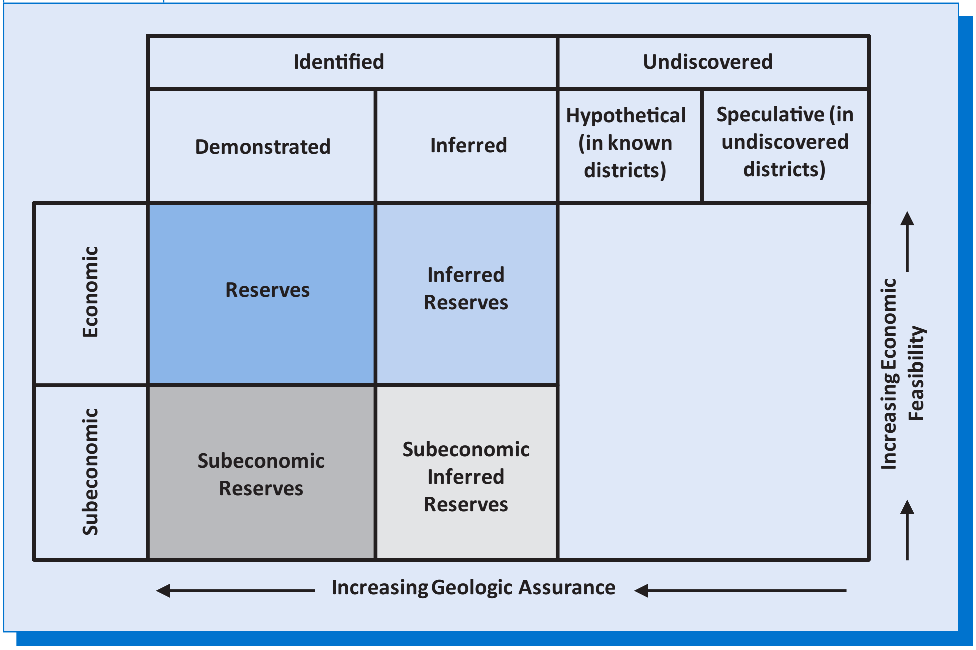
economic reserves (of a resource) the quantity of a resource that can be extracted profitably based on current prices and technology.

physical reserves (of a resource) the total quantity of a resource that is available, without taking into account the economic feasibility of extraction.

resource lifetime an estimate of how long a nonrenewable resource is expected to last given assumptions about prices, technology, and depletion rates.

A mineral resource such as copper is classified through a combination of geologic and economic measures (Figure 17.1).

Figure 17.1 Classification of Nonrenewable Resources



Sources: Rocky Mountain Institute, http://www.rmi.org/RFGraph—McKelvey_diagram_for_coal_gas_resources.

Note: Several resource classification schemes have been developed that differ slightly from the one above. See, for example, U.S. Bureau of Mines and U.S. Geological Survey, 1976.

In geological terms, resources are classified in terms of the degree of certainty about the availability of the resource, shown as the horizontal dimension in Figure 17.1. **Identified reserves** are those whose quantity and quality are already known, but with varying degrees of confidence. Those identified with the highest degree of confidence are **demonstrated reserves**, meaning the quantity is generally known with a high degree of certainty. A lower degree of confidence is assigned to **inferred reserves**, which are estimated based on geological principles but not accurately measured. In addition, **hypothetical and speculative reserves** are yet undiscovered, but are likely to exist in different geological regions.

Economic factors create another dimension to resource classification, shown vertically in Figure 17.1, with the most economically profitable resources at the top. Resources of high enough quality to be profitably extracted with current prices and technology are identified as economic reserves. **Subeconomic resources** are those whose costs of extraction are too high to make production worthwhile, at least with current prices and technology. However, if prices rise or extraction technologies improve, it may become profitable to exploit these deposits. Note that undiscovered reserves are not counted toward economic reserves, as their existence is uncertain. Data on reserves normally reflect only the quantities that are demonstrated and economic.

identified reserves the quantity of a resource that has been identified with varying degrees of confidence; includes both economic and subeconomic reserves.

demonstrated reserves resources that have been identified with a high degree of confidence, and who quantity is known with some certainty.

inferred reserves resources that have been identified with a low degree of confidence, and whose quantity is not known with certainty.

hypothetical and speculative reserves the quantity of a resource that is not identified with certainty but is hypothesized to exist.

One measure of the availability of nonrenewable resources is a **static reserve index**. A static reserve index simply divides reserves (demonstrated and economic) by the current annual rate of use to get an estimate of resource lifetime:

$$Expected\ Resource\ Lifetime = \frac{Economic\ \ Reserves}{Annual\ \ Consumption}$$

The fact that resource reserves can be expanded in both geological and economic dimensions renders projections using a static reserve index unreliable. Also, current consumption is not necessarily a good indication of future use. Because of growing population and economic output, we can expect nonrenewable resource demand to normally grow—although substitution, changing consumption patterns, and recycling will affect rates of growth. An **exponential reserve index** assumes that consumption will grow exponentially over time, leading to more rapid resource exhaustion.

subeconomic resources term used to describe mineral resources that cannot be profitably extracted with current technology and prices.

static reserve index an index that divides the economic reserves of a resource by the current rate of use for the resource.

exponential reserve index an estimate of the availability of a mineral resource based on an assumption of exponentially increasing consumption.

Calculations made in 1972 using both static and exponential reserve indices indicated that major mineral reserves would be exhausted within several decades—projections clearly not borne out.[1] Why not? Because reserves have grown with new discoveries and new extractive technologies. However, we cannot simply dismiss predictions of resource exhaustion, particularly for certain resources. Even with reserve expansion, planetary resources are ultimately limited.

The relevant question is how resource consumption, new technology, and discovery will interact to affect prices, which in turn will affect future patterns of resource demand and supply. To gain a better understanding of these factors, we need a more sophisticated economic theory of nonrenewable resource use.

17.2 ECONOMIC THEORY OF NONRENEWABLE RESOURCE USE

What determines the rate at which we extract and use nonrenewable resources? An individual firm operating a mine or other resource extraction operation is guided by the principle of maximization of **scarcity rents**, which we discussed in Chapter 5. Consider a firm that operates a bauxite mine (aluminum ore). If the firm is in a competitive industry, it is a **price taker**, selling its output at the market price, over which it has no control. It can, however, control the amount of the resource extracted during any period.

scarcity rent payments to resource owners in excess of the amount necessary to keep those resources in production.

price taker a seller in a competitive market who has no control over the price of the product.

In general, as more of the resource is extracted, the marginal cost of extraction will eventually rise. Obviously, if the marginal extraction cost rises above the market price, it will not be worthwhile to produce the bauxite. Price must at least equal marginal cost to make production worthwhile. But unlike other competitive industries where price equals marginal costs in equilibrium, resource-extracting firms typically operate at an output level at which price exceeds marginal cost (Figure 17.2). While firms could make small profits on the last few units produced, they have the option of postponing extraction until future periods when the profitability of those units may be higher. Thus rather than maximizing total current profits at Q_m, long-term profit maximization may imply production at $Q*$. The forgone current profits (shaded area A) would be more than offset by higher profits in the future.

In addition to expectations about future prices and costs, prevailing interest rates will also influence firms' production decisions. Higher interest rates tend to encourage increased current production, as firms have a strong incentive to make immediate profits and invest them at the high rates. But increased production will drive down the current price of the resource, as well as reduce the available reserves and raise expected future prices. Both of these factors will shift production toward the future.

As we saw in Chapter 5, the expected outcome of this adjustment is that equilibrium is reached when firms' scarcity rents grow at the same rate as the interest rate—**Hotelling's rule**. Note that Hotelling's rule equates the rate of growth of **net price** (market price minus extraction cost), not of market price, to the interest rate. Thus information solely on resource market prices is not sufficient to test the validity of Hotelling's rule. Additional information is needed on extraction costs and external factors that may, at least temporarily, push resource rents away from the path implied by Hotelling's rule.

Hotelling's rule a theory stating that in equilibrium the net price (price minus production costs) of a resource must rise at a rate equal to the rate of interest.

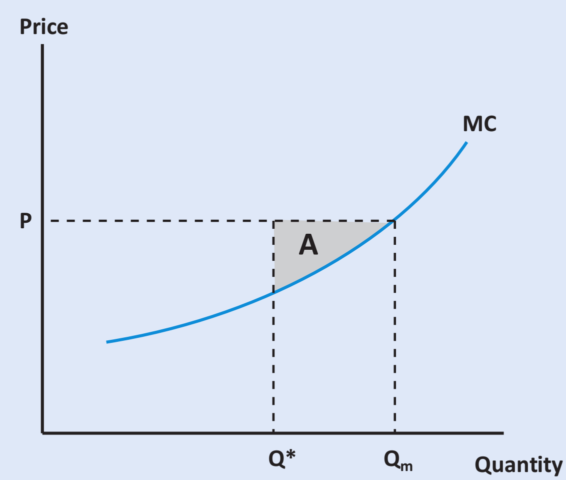
net price (of a resource) the price of a resource minus production costs.

Economists have tested the accuracy of Hotelling's rule by studying trends in resource prices, extraction costs, and other variables. A 1998 paper summarized the empirical tests of Hotelling's rule and found that these analyses:

> . . . have not completely reconciled the economic theory of nonrenewable resources with the observed data. . . . The variety of possible outcomes makes it difficult, if not impossible, to make any general predictions about the overall impact on price and extraction paths.[2]

The paper notes that the discovery of new deposits and technological progress has so far been sufficient to avoid increasing economic scarcity of nonrenewable resources. However, just because past advances have kept pace with increasing demands, there is no assurance that this will continue indefinitely. There is still a need for improved management of nonrenewable resources:

Figure 17.2 Nonrenewable Resource Production Decisions



Source: Adapted from Hartwick and Olewiler, 1998, which provides a more advanced discussion of the economic theory of nonrenewable resource extraction.

> Given the open access and public good nature of these resources and services, market interventions are necessary to prevent inefficient use of these resources. Because of this, the attention focused on the environmental impacts of nonrenewable resource use will continue to increase with increased emphasis on the details of ecological interactions and the management of global public assets.[3]

A less controversial theory of nonrenewable resource management is that higher-quality resources will be exploited first. Suppose, for example, that a firm owns two bauxite deposits, one high grade and one low grade. Marginal costs of production for the high-grade resource will be relatively low, so a high scarcity rent can be obtained by producing today. Costs of extracting the low-grade deposit are significantly higher. Even if extracting the low-grade deposit today would be marginally profitable, waiting until market prices rise or until better technology makes extraction less costly will often be a better strategy. This partly explains why resources that are subeconomic today (see Figure 17.1) can become economic in the future, possibly increasing the amount of economically recoverable reserves—at the same time that extraction has diminished the physical reserves.

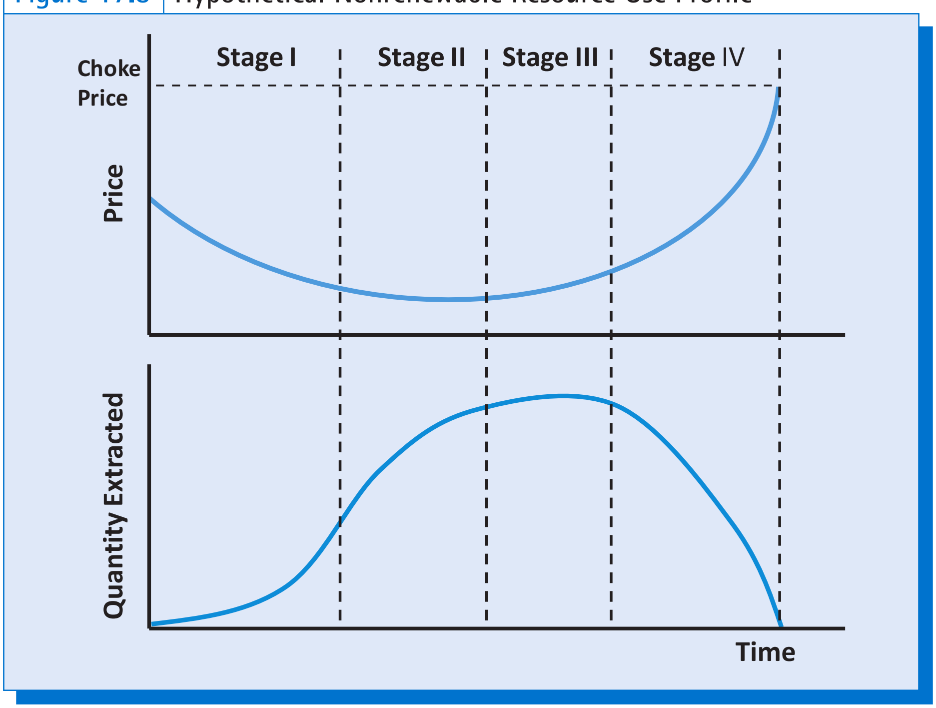
During the early stages of nonrenewable resource extraction, high-quality supplies are likely to be abundant. As exploration expands and technology improves, initially we would expect prices to decline even as extraction rapidly increases. This is shown as Stage I in Figure 17.3, which presents a stylized long-term **resource use profile** for a nonrenewable resource. Figure 17.3 shows the **price path** and **extraction path** for a resource stock being exploited over time.

resource use profile the consumption rates for a resource over time, typically applied to nonrenewable resources.

price path the price of a resource, typically a nonrenewable resource, over time.

extraction path the extraction rate of a resource over time.

Figure 17.3 Hypothetical Nonrenewable Resource Use Profile



Source: Adapted from Hartwick and Olewiler, 1998.

During Stage II, prices are fairly stable as increasing demand (tending to pull prices up) balances further discovery and technological improvement (tending to pull prices down). During Stage III, demand starts to press against resource limitations, prices begin to rise, and reserves that were subeconomic in earlier years become economic. Technological progress is no longer sufficient to offset increasing resource scarcity.

> **choke price** the minimum price on a demand curve where the quantity demanded equals zero.

As reserves are depleted even further, we finally reach Stage IV, when rising prices begin to reduce the quantity demanded. Ultimately, the price reaches the **choke price**, at which the quantity demanded falls to zero. By the time the choke price is reached, producers will have extracted and sold all economically viable reserves, although some physical subeconomic reserves will still be available. As a resource approaches its choke price, the motivation to find appropriate substitutes and raise recycling rates will increase.

Considerable controversy exists as to whether a resource profile similar to Figure 17.3 applies to most nonrenewable resources. Where it does apply, an interesting question is whether we are currently in Stage I, II, III, or IV, and therefore whether we can expect falling, stable, or rising prices in the future. We review this debate in the next section.

17.3 GLOBAL SCARCITY OR INCREASING ABUNDANCE?

A classic study from the 1960s found that most mineral resource prices fell from the Industrial Revolution through the mid-twentieth century.[4] At the same time, global nonrenewable resource consumption steadily expanded. These findings are consistent with Stages I and II of Figure 17.3. Three major factors were responsible for these trends:

- Continual resource discovery
- Improved resource extraction technology
- **Resource substitution**, such as use of plastics in place of metals

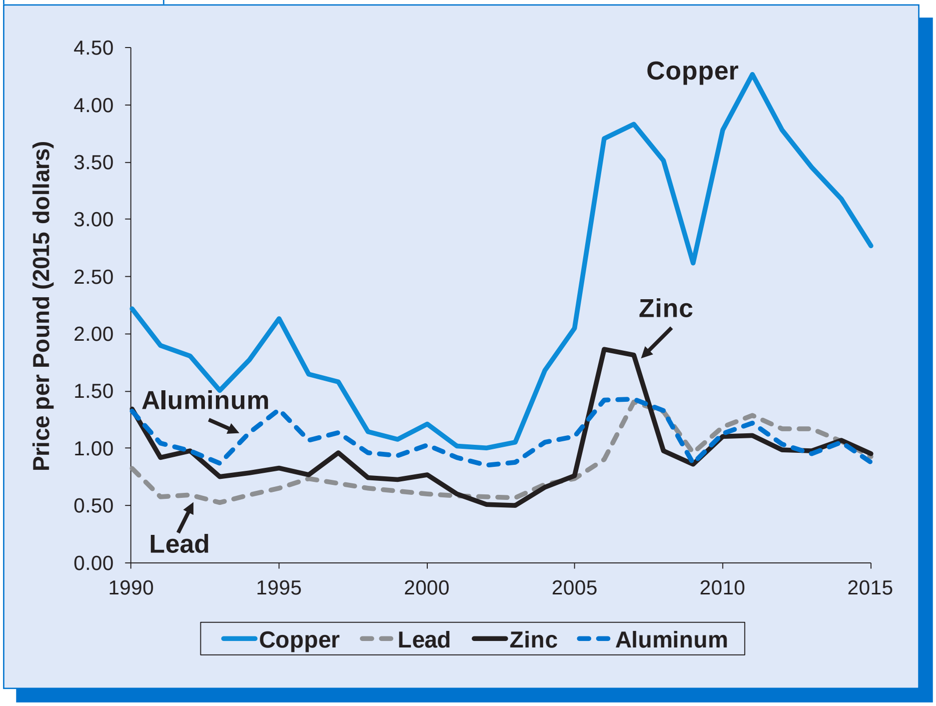
> **resource substitution/substitutability** the use of one resource in a production process as a substitute for another resource, such as the use of aluminum instead of copper in electrical wiring.

Minerals prices continued to generally decline or remain steady during the second half of the twentieth century. However, starting around 2004 the price of many minerals increased as a result of surging global demand, as shown in Figure 17.4 for the common minerals copper, lead, aluminum, and zinc. In the aftermath of the global financial crisis in 2008 and 2009, non-renewable resource prices generally declined. In real terms, the prices for aluminum and zinc were slightly lower in 2015 than they were in 1990, while copper and lead were slightly higher.

Based on these observed price paths, it seems unlikely that we have entered into Stage III yet for these minerals. Further evidence that resource shortages do not appear imminent is found by looking at data on minerals reserves. While global extraction of minerals has increased, reserves for many minerals are actually at or near record levels, as shown in Figure 17.5, for copper, lead, and zinc.[5]

Considering a broader range of minerals, Table 17.1 shows expected resource lifetimes based on current economic reserves. The static reserve indices indicate that supplies of some minerals are quite abundant, for example, lithium, aluminum, and copper. Meanwhile, reserves of lead, tin, and zinc are sufficient to meet less than 20 years of current demand.

Figure 17.4 Prices for Selected Minerals, 1990–2015



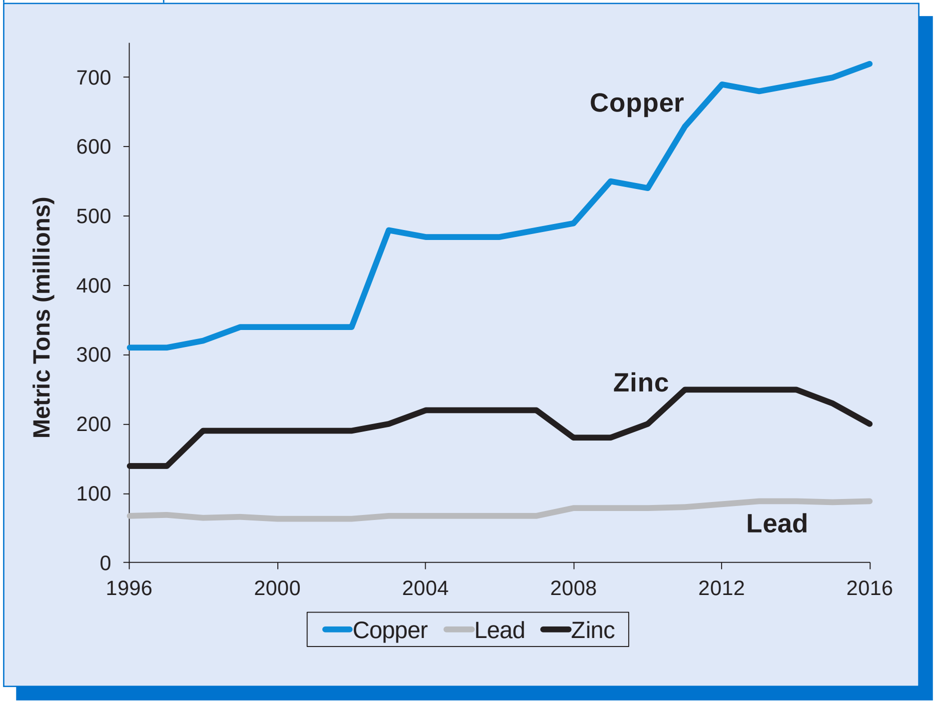
Source: U.S. Geological Survey, Minerals Commodities Summaries, various years.

But, as mentioned earlier, the usefulness of a static reserve index is limited because it fails to account for new discoveries, changes in demand, and technological change. For example, while current reserves of lead are sufficient for only about 20 years of global demand, Figure 17.5 shows that lead reserves have remained steady or increased in recent years.

In general, global mineral supplies do not appear to be running low in the short term, although this does not imply that we should not worry about future supplies. According to a recent analysis:

> Global mineral reserves are adequate to supply world mineral demand for the next 50 years, at least in theory. Presently estimated global mineral reserves are 20 to almost 1,000 times larger than present annual production, depending on the commodity of interest. . . . Exactly when supply will become the dominant factor is difficult to predict and will undoubtedly vary from commodity to commodity and be heavily dependent on the form and cost of industrial energy. In fact, the failure of earlier predictions of mineral supply and demand relations, many of which foresaw mineral shortages by the year 2000, has led to a dangerous complacency about future world mineral supplies and might lead us to misinterpret these reassuring reserve figures.
>
> Although mineral reserves are large and seem adequate for the next 50 years or so when considered as a single global number, it is important to remember that these reserves are made up of many separate deposits, all of which have to be considered in the local context of which they are a part. Each of these deposits is subject to geologic, engineering, economic, environmental, and political constraints that undergo continuous change.[6]

Figure 17.5 Global Economic Reserves for Selected Minerals, 1996–2016



Source: U.S. Geological Survey, Minerals Commodities Summaries, various years.

Table 17.1 Expected Resource Lifetimes, Selected Minerals

Mineral	2015 Global Production (thousand metric tons)	Global Reserves (thousand metric tons)	Expected Resource Lifetime, Years (static reserve index)
Aluminum	274,000	28,000,000	102
Cobalt	124	7,100	57
Copper	18,700	720,000	39
Iron ore	3,320,000	85,000,000	26
Lead	4,710	89,000	19
Lithium	32.5	14,000	431
Mercury	2.34	600	256
Nickel	2,530	79,000	31
Tin	294	4,800	16
Tungsten	87	3,300	38
Zinc	13,400	200,000	15

Source: U.S. Geological Survey, 2016.

Note: Aluminum data for bauxite ore, the primary source of aluminum.

A similar sentiment is expressed by the British Geological Survey, which also notes the potential problem of environmental impacts.

> As demand for metals and minerals increases, driven by relentless growth in the emerging economies in Asia and South America, competition for resources is growing. Human factors such as geopolitics, resource nationalism, along with events such as strikes and accidents are the most likely to disrupt supply. Policy-makers, industry and consumers should be concerned about supply risk and the need to diversify supply from Earth resources, [to] recycling more and doing more with less, and also about the environmental implications of burgeoning consumption.[7]

According to a 2015 analysis, the minerals with the greatest risk of supply disruption include rare earth elements (mainly used in electronics), antimony (used in batteries, cables, and flame retardants), and bismuth (used in fuses and cosmetics).[8] The reserves of all three of these minerals are highly concentrated in China. Also, recycling is difficult and there are limited substitutes for each of them.

In addition to concerns about resource depletion, the environmental impacts of minerals mining are significant, and tend to increase as lower-grade ores are exploited, since these usually require more energy to process and generate more waste per unit of mineral extracted. We now turn to the environmental impacts of mining in more detail.

17.4 ENVIRONMENTAL IMPACTS OF MINING

As discussed in Chapter 3, the price of a product should reflect both the private and social (or external) costs of production. While some regulations have been implemented to reduce the environmental impacts of mining:

> [T]he full social and environmental costs of mining are not included in the price of mineral products and that more may yet need to be done to bring the private and social marginal costs of production more into line.[9]

Table 17.2 presents some of the environmental impacts of minerals mining. When minerals ores are extracted from the earth, they must be processed in order to separate out the economically valuable material. The nonvaluable waste, known as **tailings**, can pollute the environment by contaminating rivers and lakes, leaching into groundwater, or being blown into the air (see Box 17.1). The refining of mineral ores, known as **smelting**, is also a potential source of environmental damage, including air and water pollution.

tailings the unwanted material from mining operations, often highly toxic.

smelting the production of a metal from a metallic ore.

Unfortunately, no economic analyses estimate the total externality costs of mining. Some recent examples of mining activities that have caused significant environmental impacts include:

- *Gold mining in the Peruvian Amazon*: Small-scale illegal gold mining relies on highly toxic mercury to extract gold from the rocks. In addition to the human health impacts, at least 2,000 square miles have been deforested as a result of mining.[10]
- *Phosphate mining in Nauru:* About 80 percent of the small island country has been strip mined. By 2000, the phosphate reserves were essentially depleted. Not only has the island become an environmental catastrophe, but the mining revenues were placed in a trust fund that was depleted due to poor investments and corruption.[11]

Table 17.2 Potential Environmental Impacts of Mining

Activity	Potential Impacts
Excavation and ore removal	• Destruction of plant and animal habitat, human settlements, and other features (surface mining) • Land subsidence (underground mining) • Increased erosion; silting of lakes and streams • Waste generation • Acid drainage and metal contamination of lakes, streams, and groundwater
Ore concentration	• Waste generation (tailings) • Organic chemical contamination • Acid drainage and metal contamination
Smelting/refining	• Air pollution (including sulfur dioxide, arsenic, lead, cadmium, and other toxics) • Waste generation (slag) • Impacts of producing energy (most energy used for mineral production goes into smelting and refining)

Source: Young, 1992.

Box 17.1
MINING DISASTER IN BRAZIL

Tailings are the wastes left over after the valuable minerals have been removed from mined materials. While mining operations are underway, tailings are commonly stored in ponds created by building dams. Tailings ponds can be environmentally damaging when the toxic water stored in them slowly leaks out, either across the surrounding land or underground to an aquifer.

Most damaging of all is when the dam containing a tailings pond fails, releasing large amounts of waste into the environment. One of the worst such failures occurred in November 2015, when a tailings dam burst in the Brazilian state of Minas Gerais. Millions of tons of toxic sludge spilled out of the tailings pond, traveling 600 kilometers before entering the region's most important river, the Rio Doce, killing millions of fish and polluting water supplies. The spill killed about 20 people and left hundreds homeless. Ecologists estimate it will take 10 to 50 years for the local ecosystems to recover.

The Brazilian president, Dilma Rousseff, described the spill as "the worst environmental disaster Brazil has ever seen" and blamed the "irresponsible action of the company." While the company responsible, Samarco, was fined $265 million, the Brazilian government is seeking more than $5 billion in damages. The disaster seems to be a result of lax environmental regulations. Before a 2013 decision allowing Samarco to increase the height of the dam that eventually failed, an environmental institute in Brazil was already expressing concerns about the safety of the dam, and recommended a "dam break analysis."

Dante Pesca, a member of a UN working group that studied the region, noted that, "When it comes to development, the economic side usually prevails over the social and environmental." He also mentioned that mining fines tend to be relatively low, and are often not fully paid, thus creating an incentive for companies to take risks. According to the UN working group, of the more than 750 tailings dams in Minas Gerais, 40 of them are considered "at risk."

Sources: Cowie, 2016; Phillips, 2015.

- *Copper and gold mining disaster in Papua New Guinea:* Since 1984 the Ok Tedi Mine in Papua New Guinea has been discharging nearly 100 million tons of tailings annually into local rivers. The tailings waste has polluted downstream fisheries and agricultural land, disrupting the lives of 50,000 people. In 2013 the national government seized control of the mine, ostensibly to reduce the environmental damage. However, the seizure of the mine coincided with legislation that prevents people from suing the mine's private operators for past damages.[12]

Another environmental problem is contamination from abandoned mines. For example, in the United States:

> [O]ne legacy of hardrock mining in the United States is the presence of many abandoned mines around the West. Some of these sites are causing severe environmental problems. The chief one is acid drainage, contaminated water that leaks from the mines into streams and rivers. Current government policies to cope with these abandoned mines are counterproductive. . . . Public reclamation of old sites does occur, but the available funds have many restrictions that keep them from being used efficiently. The total amount of money available from these sources is small compared to the apparent need.[13]

Reforming Mining Policies

The primary mining law in the United States is the **General Mining Act of 1872**. Little changed since the mid-nineteenth century, the Act allows the extraction of minerals from many public lands without royalty payments to the government. Mining rights are preserved as long as the claimant performs $100 of drilling or excavating in a year.[14] Some public lands can be purchased by individuals or corporations for a *maximum* of $5 per acre—prices that were set in 1872 and have never been adjusted. Since the Act was passed, more than 3 million acres of public lands have been purchased by mining interests, an area the size of Connecticut. The Act contains no provisions for environmental damage, although some regulations have been enacted since then. Numerous attempts to modernize the Act have failed (see Box 17.2).

> **General Mining Act of 1872** a U.S. federal law that regulates mining for economic minerals on federal lands.

One policy to address mining pollution is a Pigovian tax, as discussed in Chapter 3. However, a tax levied in proportion to mining pollution would be difficult to implement because of the problems involved in accurately measuring mining pollution. A tax could instead be levied on a mine's mineral output, rather than directly on pollution. But the problem with this proposal is that a firm would have no clear incentive to reduce its pollution for a given level of output, as it would be taxed the same amount.

Instead of a tax, requiring a mining company to post a bond before being allowed to mine would provide the public with compensation in case of environmental damage. The bond would need to be large enough to cover potential cleanup costs. For example, the state of Colorado required a $2.3 million cash bond from a company operating a gold mine, but when the company went bankrupt in 1992 the bond was insufficient to pay for cleanup costs of more than $150 million.[15]

Mining pollution is a problem that may be best addressed through effective standards and operational requirements. Nearby surface water and groundwater can be constantly monitored to identify contamination problems early. Stronger regulations can mandate certain practices for the management of tailings. In addition, mining activities can be limited by increasing the recycling of existing metal products. We consider the potential for recycling in the next section.

Box 17.2
A MINING LAW WHOSE TIME HAS PASSED

The General Mining Act of 1872 was designed to spur development of the western United States by giving mining precedence over other uses of federal lands. Mining claims for copper, gold, uranium, and other minerals cover millions of acres, and the Act makes it extremely difficult to block mining regardless of the potential environmental impacts. Rising mineral prices in recent years have spurred an increase in mining claims under the Act.

Oregon's Chetco River is one example. The river's clear waters teem with wild trout and salmon. In 1998 Congress designated the Chetco a national wild and scenic river "to be protected for the benefit of present and future generations." But starting in 2002 a real estate developer began staking gold mining claims along supposedly protected sections of the river. The developer proposed using suction dredges that would vacuum up the river bottom searching for gold, muddying water and disrupting clean gravel that salmon need to spawn. Without an act of Congress, environmentalists and state legislators were essentially powerless to prevent the mining because of the 1872 law. The mining plans were only stopped when the developer failed to pay an annual filing fee in 2011.

As Michael P. Dombeck, a former chief of the Forest Service, explained to a Senate committee in 2008, "It is nearly impossible to prohibit mining under the current framework of the 1872 mining law, no matter how serious the impacts might be."

According to the Environmental Protection Agency (EPA), streams in 40 percent of western watersheds are polluted by mining. A 2006 analysis of 25 western mines by the environmental group Earthworks concluded that more than three-fourths caused water contamination. Under the Mining Act, mine owners can abandon a mine without any responsibility for subsequent environmental damages. The EPA has estimated that it will cost $20 to $54 billion to clean up abandoned mine sites.

Potential reforms to the Act include giving the government the power to prevent mining based on a complete review of environmental impacts, clear environmental standards for operating mines, a fund for mine cleanup to be paid by mine operators, and charging royalty fees that reflect the market value of the minerals. In both 2007 and 2009 reforms were proposed in Congress to institute royalty fees on mining claims, and using a share of the revenue to clean up polluted abandoned mines. In both cases the reform proposals failed as a result of lobbying and opposition by legislators from mining states.

Sources: Hughes and Woody, 2012; https://en.wikipedia.org/wiki/Chetco_River.

17.5 THE POTENTIAL FOR MINERALS RECYCLING

In Stages I and II of the resource use profile in Figure 17.3 there is little incentive for recycling as the price of the **virgin resource** is falling. But in Stage III, when prices begin to rise but demand remains high, recycling is likely to become more economically attractive. Over time, the proportion of total demand met from recycled material rather than virgin resources will rise as extraction costs rise in Stages III and IV. Even with decreasing extraction of the virgin resource in Stage IV, the total supply of a mineral need not fall, with efficient recycling.

virgin resource a resource obtained from nature, as opposed to using recycled materials.

This is illustrated in Figure 17.6. The dashed line shows a resource extraction path without recycling, similar to the one shown in Figure 17.3 but only for Stages III and IV. Now we consider the effect of minerals recycling. At the start of Stage III, recycling is low, as virgin materials can still be obtained relatively cheaply. But as extraction costs of the virgin resource increase, and demand continues to rise, more of the total supply is met from recycled materials. Eventually, most of the total supply is met from recycled materials rather than the virgin resources. Note that recycling allows us to continue to use the virgin resource for a longer period, but at low rates. Recycling may provide a steadily increasing proportion of the resource supply. With technological improvements and high recycling rates, the choke price occurs later, if at all.

The shift toward recycled material would occur even earlier if prices reflected environmental externalities. In general, the environmental impacts are reduced by producing a product with recycled materials than virgin materials. For example, obtaining aluminum from recycled beverage cans requires 90–95 percent less energy than extracting virgin aluminum.[16] Using recycled steel reduces energy requirements by about three-fourths.[17] Thus a tax based on environmental externalities would increase the relative advantage of recycled materials over virgin resources.

Another alternative to a virgin resource is a **backstop resource**, defined as a resource that can substitute for the original product but at a higher price. Thus we can view the choke price as the price at which it becomes cheaper to shift production to a backstop resource. With effective recycling, the shift to a backstop resource would be postponed or possibly eliminated.

> **backstop resource** a substitute resource that becomes a viable alternative after the price of the initial resource reaches a certain high price.

Recycling resources today reduces both present and future costs from primary resource use. The recycling process also has its own costs, including capital costs of recycling facilities and labor, transportation, and energy costs. It makes sense, therefore, to examine the economics of recycling and its effects on resource use in more detail.

The Economics of Minerals Recycling

In theory, effective recycling could significantly extend the lifetime of many nonrenewable resources. However, recycling has both economic and physical limits.

The **second law of thermodynamics** (the principle of increasing entropy, discussed in Chapter 9) implies that perfect recycling is impossible. Some loss or degradation of material will always occur during the process of fabrication, use, and recycling. In addition, recycling requires new inputs of energy. In economic terms, we must compare recycling costs to the costs of using virgin materials to determine when recycling will be both physically possible and economically advantageous.

> **second law of thermodynamics** the physical law stating that all physical processes lead to a decrease in available energy, that is, an increase in entropy.

Figure 17.7 shows the economics of recycling, considering the perspectives of an industry and of social welfare. The *x*-axis indicates the proportion of industrial demand for a resource met from recycled materials. Our analysis assumes that the marginal cost of recycled materials (MC_r) is initially low, but as we approach a theoretical 100 percent recycling, increasing the proportion of recycled materials becomes difficult and expensive. The marginal private cost of extracting a virgin resource (MPC_v) is also initially relatively low, as the cheapest reserves are extracted first. Reserves that are deeper underground or of lower quality become increasingly expensive to extract. (The MPC_v curve should be read from right to left, showing increasing reliance on virgin materials at lower levels of recycling.)

Reading from left to right, it makes sense for the industry to increase its reliance on recycled materials as long as the marginal costs are lower than the marginal costs of the virgin resource. In this simple example, the industry will minimize its production costs when it relies upon recycled materials for 40 percent of its supply.

Figure 17.6 Impact of Recycling on Virgin Resource Extraction Path

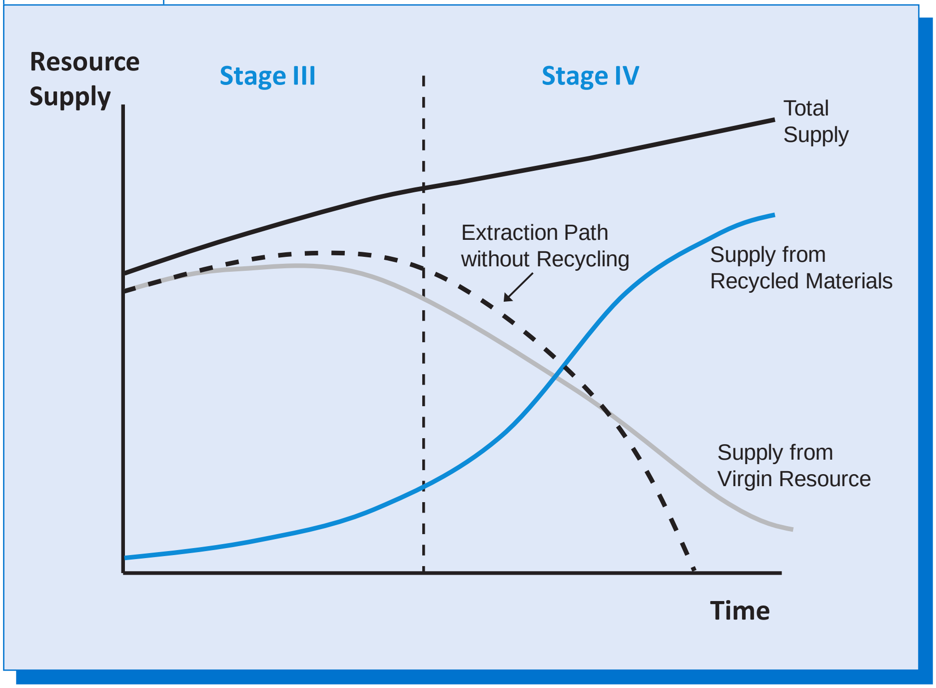
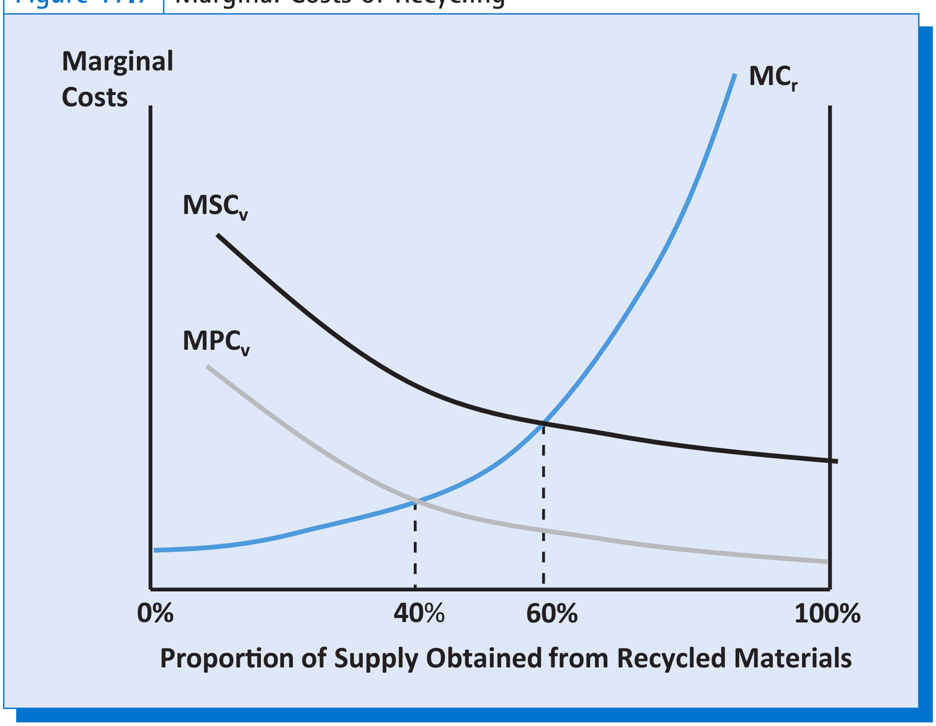


Figure 17.7 Marginal Costs of Recycling

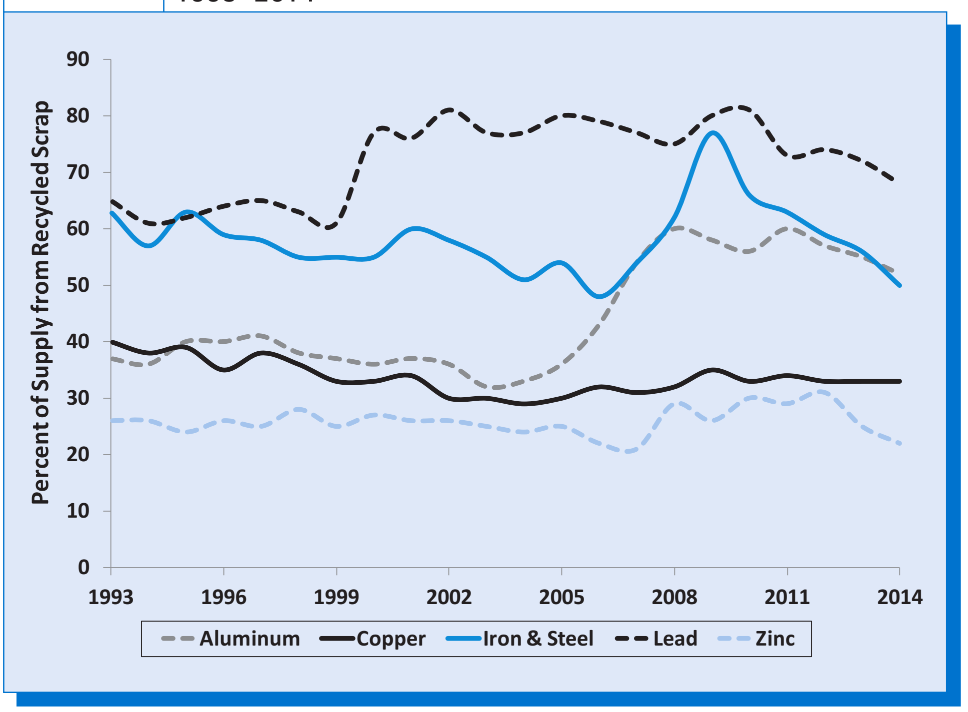


From the social perspective, we need to also consider the environmental externalities. The MSC_v curve shows the marginal social cost of extracting the virgin resource, with the difference between MSC_v and MPC_v representing the additional environmental externalities associated with the extraction of the virgin resource, as opposed to recycling. Thus the socially optimal level is to rely on recycled materials for 60 percent of the total supply. Note that this is similar to adding externalities to the private supply cost to obtain a social optimum, as we did in Chapter 3. Internalization of environmental costs through a tax on virgin resource extraction could achieve this social optimum. As the marginal costs of recycled and virgin materials shift over time, even further reliance on recycling may be justified.

The potential to recycle specific minerals varies based on technology, infrastructure, and economics. Figure 17.8 presents the percent of total supply met from recycled scrap for select minerals in the United States over time. We see that the reliance on recycled scrap varies significantly, from 70 percent or more for lead, down to about 25 percent for zinc. Recycling rates for some minerals, such as copper and zinc, have been relatively stable over time. For aluminum and iron and steel, recycling rates rose for several years in the 2000s before declining more recently. Considering total minerals supply, the share of supply met from recycled scrap increased from about half to three-fourths from 2003 to 2009.[18] But since then minerals recycling has declined, falling back down to 50 percent of supply by 2014.

Changes in the recycling rates for different minerals are often reflective of complex economic factors. Much of the scrap metal obtained in the United States is exported, with a large share sent to China in recent years. In the twenty-first century minerals demand in China has been expanding rapidly, while minerals demand in the rest of the world has been relatively stable.[19]

Figure 17.8 Scrap Metal as a Percentage of U.S. Supply, Select Minerals, 1993–2014



Source: Various editions of *Minerals Yearbook*, USGS.

In 2009 about half of the scrap metal supply in the U.S. was exported.[20] But the global financial crisis and eventual economic slowdown in China reduced the demand for scrap metal exports, leading to a decline in prices—a drop of more than 40 percent between 2012 and 2015. A stronger U.S. dollar has also reduced the demand for American scrap metal exports, and importing countries have been shifting their demand to countries with weaker currencies, such as Russia and Ukraine.[21]

Thus even though the environmental benefits of metal recycling can be significant, economic factors often result in recycling rates that are below optimal levels. We next consider policies that could increase minerals recycling rates.

Policies to Promote Minerals Recycling

As we have seen many times throughout the text, well-designed economic policies can result in more efficient outcomes and improved environmental quality. Minerals recycling is one policy area where policy reform is sorely needed. According to the United Nations,

> in spite of significant efforts in a number of countries and regions, many metal recycling rates are discouragingly low, and a "recycling society" appears no more than a distant hope. This is especially true for many specialty metals which are crucial ingredients for key emerging technologies. Policy and technology initiatives to transform this situation are urgently needed.[22]

technological lock-in the tendency of an industry or society to continue to use a given technology despite the availability of more efficient or cheaper technologies.

government procurement programs that guarantee a certain government demand for a good or service.

What kinds of policies would best promote increased recycling of nonrenewable minerals? Policy options for increasing recycling include the following:

- *Altering public policies that encourage rapid resource extraction*. Governments often make mineral resources available for exploitation at extremely low cost. As mentioned above, the General Mining Act of 1872 clearly needs to be reformed. In addition to lost revenues, low prices for valuable resources promote resource overuse and excessive social costs.
- *Imposing taxes on the use of primary resources*. As Figure 17.7 shows, internalizing environmental costs through a tax promotes increased use of recycled materials. However, because the cost of virgin materials usually represents only a small portion of the final product cost, a tax alone may have little effect on consumption pattern.[23]
- *Combining market incentives for recycling with measures to promote the technology and infrastructure needed for recycling systems*. A phenomenon known as **technological lock-in** leads an industry that has once acquired a certain kind of plant and machinery—in this case production technology using nonrenewable resources—to continue investing in the same kind of plant. Changing over a whole industry from one production system to another involves heavy costs and requires a significant amount of initial capital. Tax incentives, support for research and development of recycling technologies, and **government procurement**—programs that guarantee a certain government demand for recycled materials—can help to jump-start this process.
- *Requiring increased manufacturer "take back" responsibility*. Recycling of metals is commonly left to consumers and disposal companies. A different approach is to place a greater share of the responsibility for recycling on the manufacturer. The Green Dot recycling system, initiated in Germany in the 1990s and subsequently extended to many other

European countries, funds recycling efforts through a fee imposed on producers. In some cases the manufacturer is obliged to take back discarded products once consumers are finished with them. Not only does this increase recycling rates, but it also encourages producers to make products with less material and that can be easily recycled.

Greater information on the global status of metals recycling is also needed. Global recycling rates for many minerals are unknown.[24] Uniform measures of recycling performance can be used to inform policy discussions and track progress over time. In addition to economics and technology, increased recycling also depends upon social changes to make recycling habitual. Thus information campaigns and efforts to make recycling easy can also be effective.

Summary

Nonrenewable resources are limited in supply, but available reserves can be expanded either by new discovery or technological improvements. Concerns over the exhaustion of major nonrenewable mineral resources have so far not been borne out. Despite growing demand, new discoveries and improved technology have increased available reserves of key minerals.

Prices for most minerals have generally been stable in recent years, also suggesting that supply constraints are not significant.

Even though reserves are typically adequate, improved management of mineral resources is needed to address environmental impacts. The mining process generates large quantities of toxic waste and has extensive negative environmental effects on land and water. Internalizing the full environmental cost of resource recovery would encourage a shift to renewable resource use or recycling, rather than increased consumption of virgin resources. Although complete recycling is impossible, recycling rates for most major metals can increase considerably. In addition to extending nonrenewable resource lifetimes, recycling significantly reduces the environmental damage associated with the production of virgin materials.

Public policies to promote recycling include raising royalty payments for access to minerals on public lands, internalizing environmental costs through taxes on virgin resource use, developing technology and infrastructure, and government procurement of recycled products.

Key Terms and Concepts

backstop resource
choke price
demonstrated reserves
economic reserves
exponential reserve index
extraction path
General Mining Act of 1872
government procurement
Hotelling's rule
hypothetical and speculative reserves
identified reserves
inferred reserves
net price (of a resource)
nonrenewable resources
physical reserves (of a resource)
price path
price taker
resource lifetime
resource substitution
resource use profile
scarcity rent
second law of thermodynamics

smelting

static reserve index

subeconomic resources

tailings

technological lock-in

user costs

virgin resource

Discussion Questions

1. Is scarcity of nonrenewable resources a major problem? What kinds of physical and economic measures are relevant to understanding this issue, and in what ways can some of the measures be misleading? What do you think are the main issues relating to nonrenewable use?
2. How do you think mineral prices are likely to rise or fall in the future? Which factors do you think will determine future mineral prices?
3. Some critics of minerals recycling programs have argued that they are uneconomic because they cost more than simply discarding unwanted metals in landfills. Which economic factors would you use to evaluate this argument? What relationship exists between recycling incentives for end-users and incentives for manufacturers to use recycled materials? How can environmental costs be internalized at various stages of the production cycle?

Notes

1. Meadows *et al.*, 1992.
2. Krautkraemer, 1998, p. 2102.
3. Ibid., p. 2103.
4. Barnett and Morse, 1963.
5. Comparable reserve data for aluminum were not available.
6. Kesler, 2007, p. 58.
7. British Geological Survey, Risk List 2012, www.bgs.ac.uk/mineralsuk/statistics/riskList.html.
8. British Geological Survey, 2015.
9. Darmstadter, 2001, p. 11.
10. Ashe, 2012.
11. https://en.wikipedia.org/wiki/Phosphate_mining_in_Nauru.
12. https://en.wikipedia.org/wiki/Ok_Tedi_environmental_disaster.
13. Buck and Gerard, 2001, p. 19.
14. General Accounting Office, 1989.
15. Buck and Gerard, 2001.
16. New Jersey Department of Environmental Protection, www.state.nj.us/dep/dshw/recycling/env_benefits.htm.
17. University of Massachusetts, Amherst, Office of Waste Management, http://www.umass.edu/recycle/recycling_benefits.shtml.
18. Minerals recycling statistics from various editions of the Minerals Yearbook, published annually by the U.S. Geological Survey.
19. IMF, 2015.

20. USGS, 2010.
21. Ibid.
22. UNEP, 2011, p. 23.
23. See Ackerman, 1996, Chapter 2.
24. UNEP, 2011.

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Web Sites

1. **http://minerals.usgs.gov/minerals/**. The web site for the Minerals Resource Program of the U.S. Geological Survey. The site includes links to extensive technical data as well as publications.
2. **www.earthworksaction.org.** The web site for Earthworks, a nonprofit environmental organization "dedicated to protecting communities and the environment from the impacts of irresponsible mineral and energy development while seeking sustainable solutions."

CHAPTER 18

Renewable Resource Use: Fisheries

Chapter 18 Focus Questions

- What are the ecological and economic principles governing fisheries?
- Why are so many of the world's fisheries suffering from overexploitation?
- What policies can be effective in conserving and rebuilding fisheries?

18.1 PRINCIPLES OF RENEWABLE RESOURCE MANAGEMENT

The expansion of human economic activity, as we noted in Chapter 2, has had major impact on the planet's renewable natural resources. In the early twenty-first century, many of the world's major fisheries are depleted or in decline,[1] global forest area decreases by about 8 million acres per year,[2] and most major groundwater aquifers are being depleted by excessive withdrawals.[3] Clearly, management of renewable resources remains a major continuing issue. What economic and ecological principles underlie sustainable—or unsustainable—management of renewable resources?

We can view resources simply as inputs into the economic production process or, in a broader view, analyze **renewable resources** in terms of their physical and ecological characteristics, including natural equilibrium and regeneration. In some resource management approaches, these two perspectives are compatible, but in others they clash. For example, should the governing principle in managing natural systems be ecological diversity or maximum yield? The problem of integrating economic and ecological goals is essential to the management of natural resource systems such as fisheries.

The human economy relies upon natural systems for **source functions** and **sink functions**. The source function is the provision of materials for human use, and the sink function is the absorption of waste products from human activity. We have already considered aspects of these functions in dealing with agriculture and nonrenewable resources. **Sustainable management** of renewable resources involves maintaining the resource's source and sink functions in such a way that its quality and availability remain stable overtime. Although this certainly seems like a desirable goal, some forms of management tend to encourage unsustainable use.

We have already seen an example of how managing a fishery as an **open-access resource** can lead to overfishing and depletion of stocks (Chapter 4). However, management by a private owner or by a government authority can also lead to unsustainable practices. The reason lies in the difference between economic principles and ecological principles.

Economic principles of resource management include profit maximization, efficient production, and efficient intertemporal resource allocation. We saw in Chapters 4 and 5 how these principles apply in general to resource use. When we examine fisheries, forests, and water systems in more detail, we see that these economic principles are sometimes, but not always, consistent with sustainable management.

The ecological principles underlying renewable resource systems are a little more difficult to express in simple terms. One basic rule derived from ecological principles is that of **maximum sustainable yield (MSY)**—no more of the resource should be harvested or withdrawn annually than can be regenerated or replenished by the natural processes of resource cycling and the capture of solar energy.

We must also consider that most natural systems are typically complex. Fisheries typically include many species of fish as well as other forms of animal and vegetable marine life. Natural forests

renewable resources resources that are regenerated over time through ecological processes, such as forests and fisheries, but can be depleted through exploitation.

source function the ability of the environment to make services and raw materials available for human use.

sink function the ability of natural environments to absorb wastes and pollution.

sustainable (natural resource) management management of natural resources such that natural capital remains constant over time, including maintenance of both stocks and flows.

open-access resource(s) a resource that offers unrestricted access such as an ocean fishery or the atmosphere.

maximum sustainable yield (MSY) the maximum quantity of a natural resource that can be harvested annually without depleting the stock or population of the resource.

usually have a variety of tree species and provide habitat for many animal species, as well as symbiotic or parasitic insects, fungi, and microbial life. Water systems generally include different kinds of aquatic habitat, some of which, like wetlands, play a crucial role in balancing the water cycle and maintaining water quality.

Human management of natural ecosystems must, of necessity, be a compromise between economic and ecological goals. In almost every case, human use of natural ecosystems will alter their state to some degree. Even so, it is generally possible to manage ecosystems without destroying their **resilience**—defined as the capacity to recover from adverse impacts—or exceeding their maximum sustainable yield. To do so, however, requires a degree of restraint that may not be consistent with economic principles of profit maximization and economic institutions of resource ownership. In this and the next two chapters, we investigate this tension between economic and ecological principles as it applies to the management of fisheries, forests, and water systems.

resilience the capacity of ecosystem to recover from adverse impacts.

18.2 ECOLOGICAL AND ECONOMIC ANALYSIS OF FISHERIES

In our initial analysis of fisheries in Chapter 4, we viewed the fishery as a productive system whose output—fish—was an economic good. But fisheries are fundamentally biological systems, so a more complete view should start with a biological analysis and examine its economic implications.

The field of **population biology** identifies a general theory of population change for an organism, such as a species of fish, in the natural environment. Figure 18.1 shows a basic pattern of population change over time characteristic of many species in a natural state. This graph shows two paths for population change over time. Above a minimum critical population necessary for survival (X_{min}), population will grow from point A to a natural equilibrium, in balance with food supply, following a **logistic curve** of growth over time.[4]

Starting from a low base and with an abundant food supply, the population initially grows at a steady rate, in a near-exponential pattern. As population increases over time, limits on food supply and living space slow the rate of population growth. Beyond point B, known as an **inflection point**, annual growth declines and population eventually approaches an upper limit X_{max}.[5] Should the population ever exceed this limit—for example, reaching point C due to a temporary increase in available food—it will decline from point C to X_{max} after normal food supply conditions return.

If the population falls below the critical X_{min} level, it will decline to extinction (point D). This can happen if disease, predation, or excessive harvesting by humans reduces the population to an unsustainably low level. The passenger pigeon in North America provides a classic case in which excessive harvesting led to extinction of a wild species. Abundant food supply in the forests of North America once made the passenger pigeon perhaps the most numerous species on the continent. Unrestrained hunting reduced it to a few scattered remnants, which died out by the early twentieth century.

In general, species populations in a natural state are determined by the environment's **carrying capacity**—the supply of food and other life support naturally available. Human exploitation of

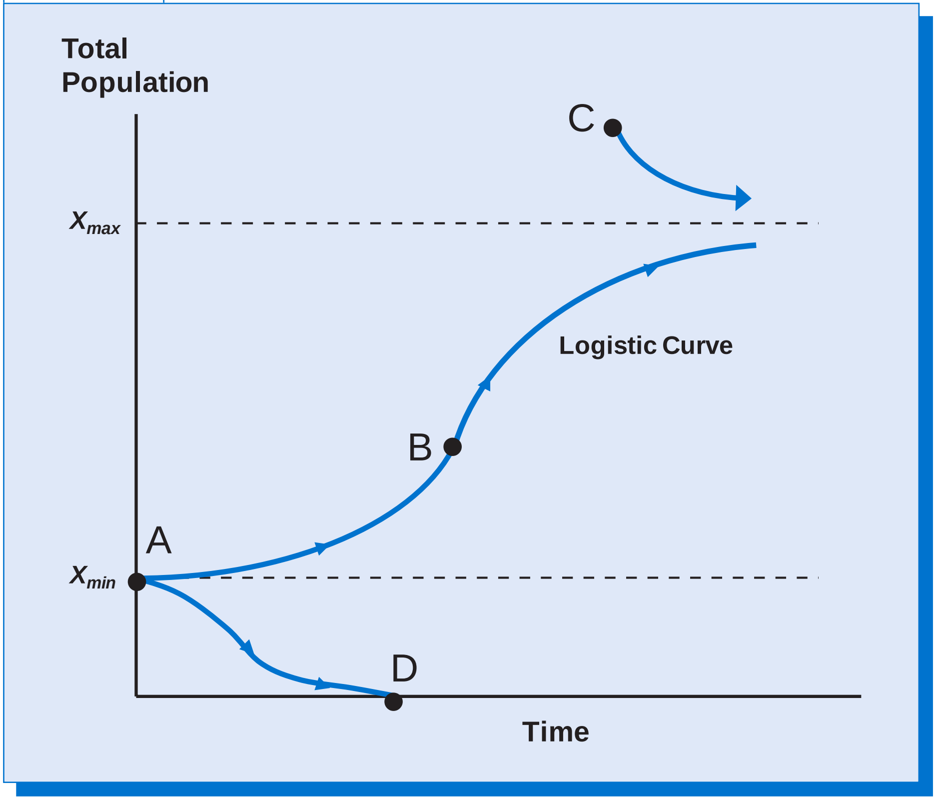
population biology the study of how the population of a species changes as a result of environmental conditions.

logistic curve/logistic growth an S-shaped growth curve tending toward an upper limit.

inflection point the point on a curve where the second derivative equals zero, indicating a change from positive to negative curvature or vice versa.

carrying capacity the level of population and consumption that can be sustained by the available natural resource base.

Figure 18.1 Species Population Growth over Time



unstable equilibrium a temporary equilibrium, for example, of the stock level of a renewable resource, that can be altered by minor changes in conditions, resulting in a large change in stock levels.

stable equilibrium an equilibrium, for example of the stock level of a renewable resource, to which the system will tend to return after short-term changes in conditions affecting stock level of the resource.

renewable resources must be consistent with this carrying capacity to avoid ecological disruption and possible population collapse.

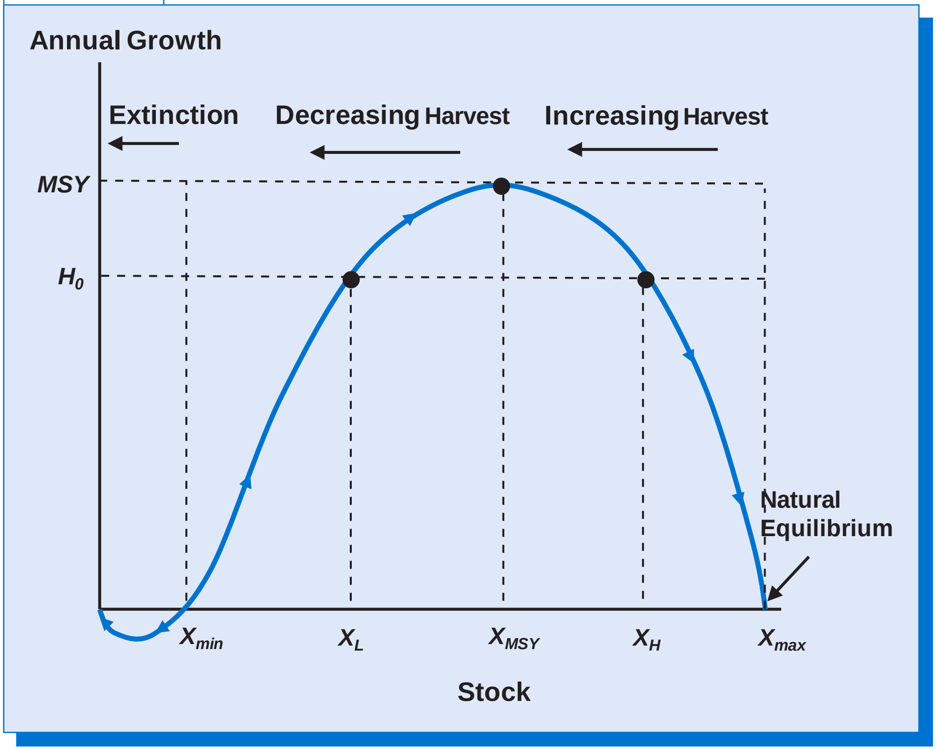
The population growth pattern shown in Figure 18.1 can be viewed in a different way by relating the stock (population size) to its growth per year (Figure 18.2). Stock size now appears on the *x*-axis and annual growth on the *y*-axis. The arrows along the curve indicate the direction of population change. When growth rates are positive (above a population of X_{min}), the population is expanding toward X_{max}, while below X_{min} it is declining toward zero.

We can now see that X_{min} is an **unstable equilibrium**. At this population, a slight increase will set the species on the road to recovery; a slight decrease will head it to extinction. Many endangered species are in this position. For example, barely enough North American whooping cranes survive to maintain a nesting population, and scientists hope to nudge the number upward to recovery. But a single major incidence of natural disaster or disease could eliminate the species.

By contrast, X_{max} is a **stable equilibrium**. In a natural state, the population will approach this equilibrium. A smaller population will grow, while a larger population will shrink. Thus while some oscillation might occur around the equilibrium, the population will not tend to explode or to crash.[6]

In this form, the population growth graph clearly shows the maximum sustainable yield (MSY) at the top of the curve. The potential sustainable harvest of fish equals the total annual

Figure 18.2 Species Population and Annual Growth



Note: MSY = maximum sustainable yield.

growth. If this amount is taken for human use, the population will remain constant. It will therefore be possible to exploit the fish stock at any population level between X_{min} and X_{max}, with the maximum possible annual harvest at a population of X_{MSY} (corresponding to point B in Figure 18.1). Note that if population is between X_{min} and X_{MSY}, the sustainable harvest can be increased by allowing the population stock to expand. But if population is between X_{MSY} and X_{max}, annual harvest can be increased by reducing the population stock.

We can also see that a particular level of sustainable annual harvest can be achieved at two different population levels. Suppose one seeks to harvest an annual amount of fish equal to H_0. This can be accomplished at two different population levels—X_L and X_H. Note that X_H represents a sustainable annual harvest with a relatively high population stock, while X_L is the same sustainable annual harvest, but with a relatively low population stock.

Deriving an Economic Analysis from Biological Principles

So far we have followed a strictly biological analysis, without considering economic implications. You might notice that Figure 18.2 bears a resemblance to Figure 4.1 from Chapter 4, which displayed the **total product** of a fishery. But Figure 18.2 differs from Figure 4.1 in an important respect—every harvest level above X_{min} in Figure 18.2 is sustainable. In other words, harvesting just the annual growth of a resource each year, and assuming no other changes to the health of the resource, such as a disease outbreak or habitat

total product the total quantity of a good or service produced with a given quantity of inputs.

tragedy of the commons the tendency for common property resources to be overexploited because no one has an incentive to conserve the resource while individual financial incentives promote expanded exploitation.

economic optimum a result that maximizes an economic criterion, such as efficiency or profits.

reduction, we can avoid the **tragedy of the commons** that was likely with the open-access equilibrium in Chapter 4.

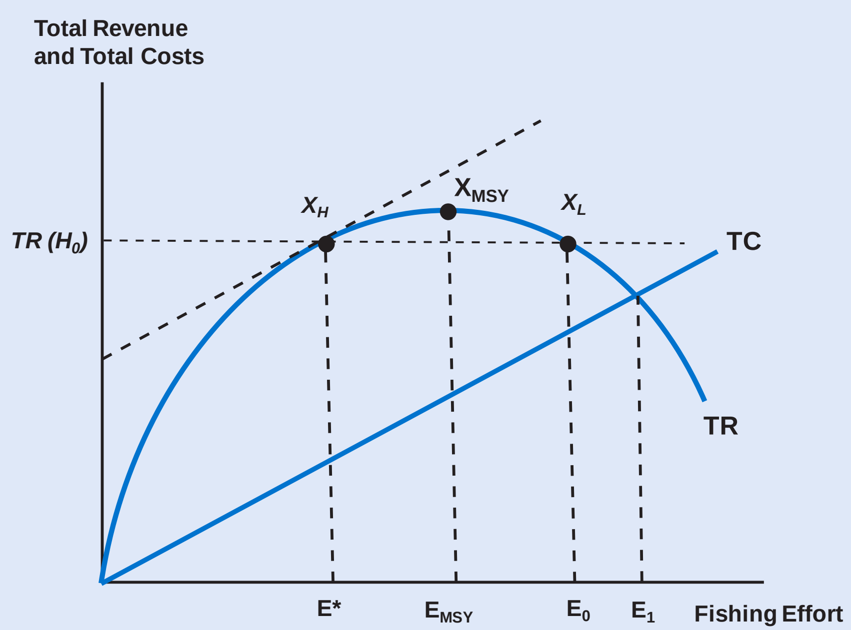
Recall from Chapter 4 that we stated the **economic optimum** was more likely to be ecologically sustainable than the open-access equilibrium. But as we did not address the biology of a fishery in Chapter 4, we had no guarantee that the economic optimum was truly sustainable. Now we can approach the management of a fishery from a combined perspective based on *both* economics and biology. Specifically, we can now determine the economically optimal level of harvest that is also ecologically sustainable.

We do this by taking essentially the same steps we did in Chapter 4. We can convert each sustainable harvest level in Figure 18.2 to a total revenue value by multiplying the quantity of fish by a price. Then we can compare total revenue to total costs to determine the harvest level that results in the highest industry profit, assuming a stable price for fish.

Take the sustainable annual harvest of H_0 from Figure 18.2, measured in tons of fish. Whether we catch this quantity of fish from a small (X_L) or large (X_H) stock of fish is irrelevant from a revenue perspective. In both cases, we achieve the same total revenue because we are harvesting the same exact quantity of fish. This is shown in Figure 18.3.

In this economic analysis, fishing effort goes from left to right on the *x*-axis and costs and revenues are on the *y*-axis. The total revenue from harvesting H_0 can be obtained in two different ways, with a relatively low or relatively high stock, as we saw in Figure 18.2. (Points X_H, X_{MSY}, and X_L in Figure 18.3 correspond to the same labeled points in Figure 18.2.)

Figure 18.3 Total Revenues and Total Costs in a Fishery



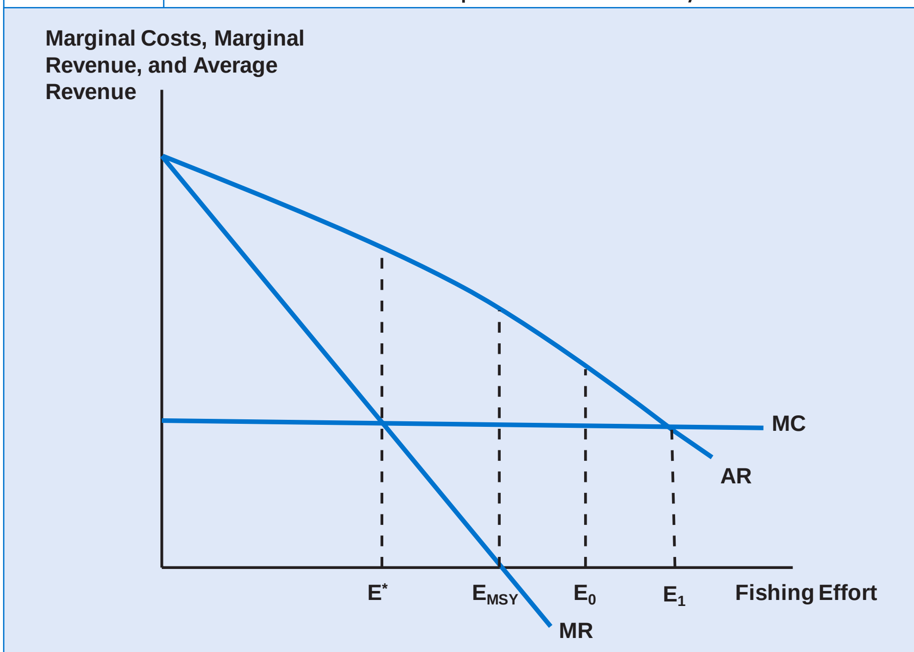
Note: Points X_H, X_{MSY}, and X_L correspond to the same labeled points in Figure 18.2. Fishing effort goes from left to right in Figure 18.3, but from right to left in Figure 18.2.

But note that the fishing effort to obtain this amount of revenue varies depending on the size of the population stock. When the fish population is relatively high, catching the annual harvest of H_0 is relatively easy as fish are abundant, and an effort of only $E*$ is required. But to catch the same quantity of fish when the population is low requires more effort, (E_0) as the density of fish is lower. Thus the total revenue curve in Figure 18.3 is essentially the mirror image of the growth curve from Figure 18.2. More effort is required to catch fish when the population stock is low as opposed to high.

As we did in Chapter 4, we assume that cost per unit of effort (e.g., per boat trip) is constant. This is shown with the linear total cost curve in Figure 18.3. Industry profits are maximized when the difference between total revenues and total costs is greatest. At this point the slopes of the two curves are equal, as shown by the dotted line parallel to the total cost curve in Figure 18.3.[7] This economic optimum is reached at an effort level of $E*$, with an annual harvest of H_0 but with a relatively high population stock of X_H. We can now see that this economic optimum is assured of also being ecologically sustainable.

We can also determine the economic optimum by comparing marginal costs and marginal revenue, as shown in Figure 18.4. As we did in Chapter 4, we can derive marginal and average revenue curves from the total revenue curve. Marginal costs are constant. The economic optimum is reached at MR = MC, with an effort level of $E*$. Total industry profits at this level of effort are higher than they are if we harvest the MSY, at an effort level of E_{MSY}, or if we harvest H_0 when the population stock is low, at an effort level of E_0. With an effort level of E_1 (identified in Chapter 4 as the open access equilibrium) total industry profits are zero.

Figure 18.4 Marginal and Average Revenues, Marginal Costs, and Sustainable Economic Optimum in a Fishery



We can draw two important conclusions from this analysis, which we'll refer to in the next section:

1. The economically optimal and ecologically sustainable level of fishing effort will be less than that required to harvest the MSY. If we increase fishing effort beyond what is needed to obtain MSY, revenues and total catch decline, while total costs increase (see Figure 18.3)—clear evidence of economic inefficiency.
2. The economically optimal and ecologically sustainable level of fishing effort will be obtained when fish population stocks are relatively high. Declining fish stocks would provide evidence both of economic inefficiency and ecological unsustainability.

18.3 THE ECONOMICS OF FISHERIES IN PRACTICE

How can we take these theoretical principles and apply them to real world fisheries? In particular, how can we determine if current fishing levels are economically efficient and ecologically sustainable? The key to answering this is to compare fishing effort to harvest levels. Consider a fishery in a relatively unexploited state, such as the cod fishery in New England when the European colonists arrived.[8] The fishery population would be at its natural equilibrium—X_{max} in Figure 18.2. As Europeans began harvesting cod, moving right to left in the graph, the population declined, but this led to a *higher* annual growth of fish. This is because a somewhat smaller stock of fish, with an unchanged food supply, can reproduce more rapidly. Moving from a population stock of X_{max} to X_H, and only harvesting the annual growth, economic efficiency increases and we remain ecologically sustainable.

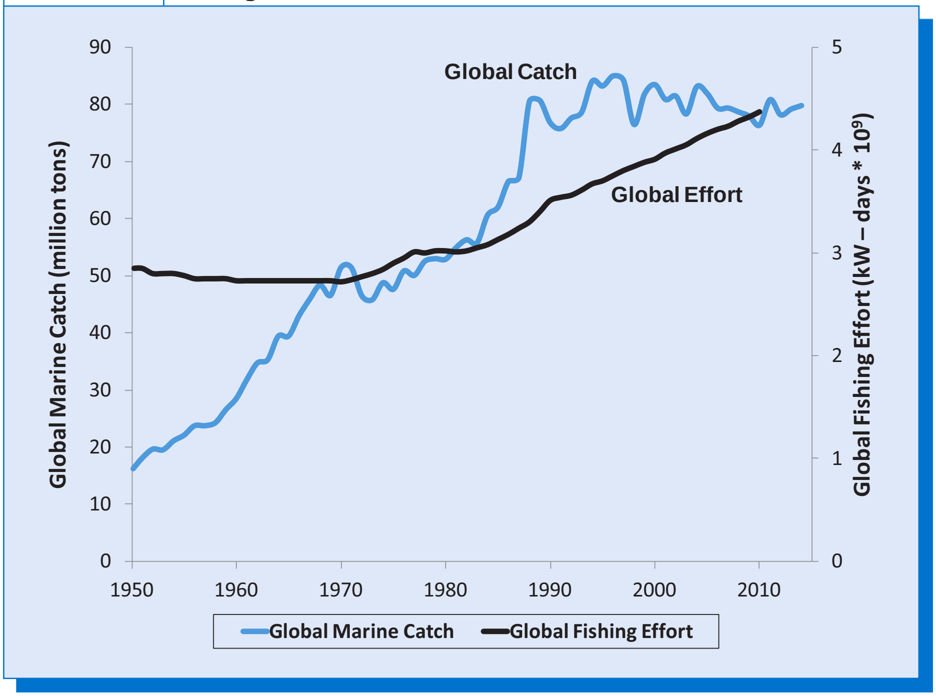
But suppose fishing effort increases such that we catch more than the annual growth. The fishery will attempt to recover through natural reproduction, but the stock will continue to decline as each year we catch more than the annual growth. As the stock falls below X_{MSY}, the density of fish becomes low such that we may need to expend more effort just to keep catching the same quantity of fish. Eventually, with continued exploitation fish density and annual growth become so low that despite any increase in effort annual fish catch keeps falling. This signals that we may be approaching X_{min}, and the ecological collapse of the fishery may be imminent.

The actual data on global fishing suggests that we have moved well beyond economically efficient and ecologically sustainable levels. Figure 18.5 compares global marine fishing catch over the last several decades to the global fishing effort, based on the power of fishing vessels and the number of days each year they spend fishing. We see that from 1950 to 1970 global fishing effort stayed relatively constant but total catch increased by over 200 percent. This suggests that fish were relatively abundant during this period, and that fishing technology was improving. Recalling our discussion from Chapter 4, this was likely a period of constant returns, when each fisher's harvest had no negative impacts on the harvest levels of others. Based on our analysis in this chapter, fishing effort during this period may have been economically efficient and sustainable.

Next, during the period from 1970 to about 1990 both effort and harvest levels were increasing. We would need more information to assess whether harvests during this period were above or below MSY, but it appears that global MSY was attained at some time during this period, since global catch has not increased further since then.

Since the 1990s fishing effort has been steadily increasing, but the global marine fish harvest has been stable or declining. As we discussed in the previous section, this is consistent

Figure 18.5 Global Marine Fishing Harvest, 1950–2014, and Global Fishing Effort, 1950–2010



Sources: Food and Agriculture Organization of the United Nations (FAO), Global Capture Production Statistics; Anticamara *et al.*, 2011.

Note: Marine catch includes marine fishes, crustaceans, mollusks, and marine mammals. The measure of kW–days$*10^9$ on the right axis is based on the power of fishing vessels and the number of days each year they spend fishing.

with a population stock that is below X_{MSY} and an economically inefficient level of harvest that may be unsustainable in the long term.

Another way to interpret Figure 18.5 is that the harvest per unit of fishing effort is declining. According to a 2012 analysis, fishing harvest per unit of effort is currently only about half of what it was in the 1950s.[9] The World Bank and FAO conclude that:

> [T]he current marine catch could be achieved with approximately half of the current global fishing effort. In other words, there is massive overcapacity in the global fleet. The excess fleets competing for the limited fish resources result in stagnant productivity and economic inefficiency.[10]

Obviously, if we could catch the same amount of fish with only half the effort, economic efficiency would increase. Further, the decline in fish harvest per unit of effort is a clear indication that fish population levels may be approaching unhealthy levels.

Fishing in open seas is a typical illustration of a situation in which the tragedy of the commons, as discussed in Chapter 4, is likely to occur. Individual fishers tend to have little incentive to practice conservation, for they know that if they do not catch the available fish, someone else probably will. Without limits in place, fishers try to catch as many fish as they

underfished term used to describe a fish stock that is being harvested below the maximum sustainable yield.

fully fished term used to describe a fish stock that is being harvested at the maximum sustainable yield.

overfished term used to describe a fish stock that is being harvested beyond the maximum sustainable yield.

possibly can. Technological improvements that make it easier to find and catch fish only make matters worse.

The increasing global fishing effort shown in Figure 18.5 has led to a decline in the biological health of many fisheries. Fisheries are classified into three categories, roughly based on a comparison between catch rates and the MSY:[11]

1. **Underfished**: harvest levels are below MSY (i.e., fish catch increases with increasing effort).
2. **Fully Fished**: harvest levels are at or near MSY.
3. **Overfished**: catch levels are above MSY (i.e., harvest levels have significantly declined from a peak without a decline in harvest effort).

Thus harvest levels can be sustainably increased only for fish stocks classified as underfished. Further increases in effort for fully fished or overfished fisheries would only lead to lower harvests. Figure 18.6 shows the status of fish stocks on a global level. In 2013 only about 11 percent of fish stocks were classified as underfished, 58 percent were fully fished, and 31 percent were overfished. We see that the percentage of stocks classified as underfished has declined from 40 percent to 10 percent since the 1970s, while the percentage of stocks classified as overfished has tripled over the same period. As we discussed in the previous section, this is further evidence of economic inefficiency and ecological unsustainability.

As a 2008 report indicates:

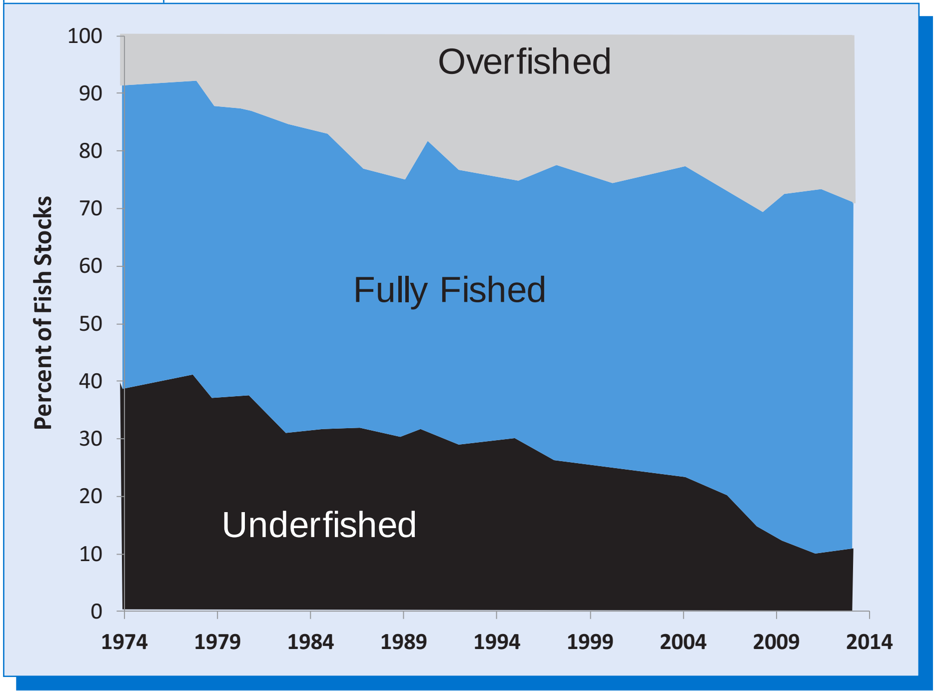
> Humans are now capable of finding and capturing marine resources in the most productive habitats around the world, and have done so better than ever before. As a result, we can no longer expect to find any hidden reserves of fish. In fact, many scientists have warned of impending collapses in fish populations within decades. While the exact timing may be debatable, the trend is not—and new stresses, including most notably, climate change, threaten to make the situation worse. . . . As the United Nations Food and Agriculture Organization (FAO) points out, "the maximum long-term potential of the world marine capture fisheries has been reached."[12]

Further increases in fishing effort are only likely to decrease yields and move us closer to the open-access equilibrium. Not only is the open-access equilibrium economically irrational, it also poses further ecological problems because modern fishing methods often cause a high death rate among nontarget species. One-fourth of all catches are discarded because they are either undersize or nonmarketable. This wasted portion of the global harvest is called "**bycatch**." A 2009 paper found that:

bycatch the harvesting of aquatic organisms other than the intended commercial species.

> 38.5 million tonnes of annual bycatch can be identified, representing 40.4 percent of the estimated annual global marine catch of 95.2 million tones. . . . [E]normous quantities of biomass are being removed from the ocean without any form of effective management. The approach outlined in this paper therefore exposes bycatch as an insidious problem of invisible fishing resulting from widespread unmanaged fisheries. . . . Few industries would tolerate levels of wastage and/or lack of sustainable management of around 40 percent.[13]

Figure 18.6 Global Trends in the Status of Fish Stocks, 1974–2013



Source: FAO, 2016b.

Although identifying the maximum sustainable yield for a fishery can help maintain an individual species, the issues of ecological sustainability are more complex. Depleting one species can lead to an irreversible change in ocean ecology as other species fill the ecological niche formerly occupied by the harvested species.[14] For example, dogfish and skate have replaced overfished cod and haddock in major areas of the North Atlantic fishery and are now themselves threatened with overfishing. Fishing techniques such as trawling, in which nets are dragged along the bottom of the ocean, are highly destructive to all kinds of demersal and benthic (near-bottom and bottom-dwelling) life. In large areas of the Atlantic, formerly productive ocean-floor ecological communities have been severely damaged by repeated trawling.

18.4 POLICIES FOR SUSTAINABLE FISHERIES MANAGEMENT

The World Bank and FAO stress the urgent need for reform of institutional fisheries:

> Failure to act implies increased risks of fish stock collapses, increasing political pressure for subsidies, and a sector that, rather than being a net contributor to global wealth, is an increasing drain on society. . . . The most critical reform is the effective removal of the open access condition from marine capture fisheries and the institution of secure marine tenure and property rights systems. Reforms in many instances would also involve the

reduction or removal of subsidies that create excess fishing effort and fishing capacity. Rather than subsidies, the World Bank has emphasized investment in quality public goods such as science, infrastructure, and human capital, in good governance of natural resources, and in an improved investment climate.[15]

From an economic point of view, **market failure** occurs in open-access fisheries because important productive resources—lakes and oceans—are treated as free resources and are therefore overused. A simple solution is to place a price on the resource.

Certainly no private owner of a small lake, for example, would allow unlimited numbers of people to fish for free, depleting the stock of fish until the resource was worthless. The owner would charge a fee to fish, yielding income for the owner (part of which might be used to restock the lake) and limiting the number of people who would fish. Although the owner's motivation would be to collect scarcity rent, the people fishing would also benefit—despite having to pay a fee—because they would have access to continued good fishing instead of suffering depletion of the fish stock.

market failure situations in which an unregulated market fails to produce an outcome that is the most beneficial to society as a whole.

Law of the Sea a 1982 international treaty regulating marine fisheries.

Exclusive Economic Zone (EEZ) the area, normally within 200 nautical miles of the coast of a country, in which that country has exclusive jurisdiction over marine resources.

An ocean fishery does not allow the private ownership solution. The oceans have been called a common heritage resource—they belong to everyone and no one. But under the 1982 **Law of the Sea** treaty, agreed to under the auspices of the United Nations, countries can claim territorial rights to many important offshore fisheries. They can then limit access to these fisheries by requiring a fishing license within their **Exclusive Economic Zones (EEZs)**, which normally extend 200 miles from their coastline.

Fishing licenses can be sold for a set fee, or a limited number can be sold at auction. In effect, this establishes a price for access to the resource. Note that we can also view this as internalizing a negative externality. Each fisher now must pay a price for the external costs imposed on one fishery by adding one extra boat. The economic signal that such a price sends will result in having fewer people enter the fishery.

This approach, however, will not necessarily solve the problem of overinvestment. A boat owner who buys a license will have added incentive to obtain the maximum catch by investing in new equipment, such as sonar devices to track fish, bigger nets, and more powerful engines to travel farther. He or she will be more likely to spend as much time as possible at sea, to earn the maximum return on the investment in the license and equipment. If all fishers do this, the depletion problem may remain serious. Governments can respond by imposing quotas on total catch, but area-wide quotas are often difficult to enforce and meet fierce resistance from fishers.[16]

One possible policy response that combines regulation with the use of market mechanisms is a system of **individual transferable quotas (ITQs)**. Like transferable emissions permits, ITQs impose a maximum limit on the quantity of fish that can be taken. Anyone purchasing such a permit can catch and sell a certain number of fish—or can sell the permit and fishing rights to someone else. Assuming that the quota limits can be enforced, the total catch from the fishery will not exceed a predetermined level.

individual transferable quotas (ITQs) tradeable rights to harvest a resource, such as a permit to harvest a particular quantity of fish.

Those fishers who can operate most efficiently will be able to outbid others to acquire the ITQs or pay a license fee.

Countries such as New Zealand and Australia have pioneered the use of transferable fishing quotas. In effect, this establishes property rights in ocean fisheries. New entrants into the industry must purchase licenses from current owners. Because overall catch is strictly limited, fish stocks have flourished, and the value of the fishing permits has steadily risen. This gives fishers an incentive to conserve, since their permit is an important asset whose value can be preserved or increased through sustainable practices. Transferable quota systems sometimes face opposition from critics who fear that corporations will take over public waters by buying up licenses. But it would be possible to protect small operators by limiting the number of permits any individual or corporation can own. [17]

Regardless of the economic policy instrument chosen, maximum allowable fishing levels must be determined in consultation with marine biologists. As shown in Figure 18.3, the optimal economic level of sustainable harvest will lie below the MSY. Thus a quota harvest level set at or below MSY can ensure ecological sustainability, as well as increase economic efficiency. In extreme cases where a fishery has been significantly depleted, a fishing moratorium may be necessary for a period to allow the stock time to recover. But even in these cases, fishing can be eventually reinstated along with careful management. Such a rebound process is currently underway in the Newfoundland cod fishery, as discussed in Box 18.1.

A more difficult problem concerns species that are highly migratory. Tuna and swordfish, for example, continually travel between national fishing areas and the open ocean. Even with

Box 18.1

SIGNS OF HOPE FOR THE ATLANTIC COD FISHERY

For hundreds of years the Atlantic cod fishery has been an important industry, bringing jobs and wealth to New England and parts of Canada. While scientists warned that the fishery was being overexploited, politicians failed to act as a result of lobbying by the industry. In Newfoundland, cod harvests began to decline by the 1980s, but the fish stock still appeared relatively healthy and no regulations were implemented. Then the population plummeted 60 percent in five years, leading to a virtual cod fishing moratorium in 1992. About 40,000 people in Newfoundland lost their jobs as a result of the moratorium. Severe restrictions on commercial cod fishing were also instituted off the coast of the United States, where the cod population in 2014 was estimated to be only 3 percent of healthy levels.

Despite the moratorium, the cod stock off of Newfoundland continued to decline for several years, attributed to unusually cold waters. But since the 1990s the fishery has been making a slow recovery. From a low of only 10,000 tons in the mid-1990s, the Newfoundland cod stock was estimated to be 300,000 tons in 2015. While this was still lower than the peak population of a million tons, a 2016 report by the Canadian government indicated that within a few years the fishery will be two-thirds of the way back toward healthy levels. Warmer waters as a result of climate change actually appear to be helping the recovery, at least for now. Thus many scientists and fisherman hope that a rebirth of commercial cod fishing is possible in the foreseeable future. The number of licenses for recreational cod fishing has already been increased.

George Rose, a recently retired professor of fisheries science in Newfoundland, has called the moratorium "essential" to the recovery, and said that, "If this stock, arguably the most mismanaged and overfished worldwide, can come back. . . then with judicious management even the largest and most severely impacted marine fish stocks can potentially recover."

While fishers fought to keep harvest levels high in the past, now many fishers recognize the importance of scientific management. Bill Broderick, director of a union which represents fishery workers in Newfoundland, notes that, "We have to do things differently now, and we have to start preparing. No one is questioning the science anymore. We just don't want to see our communities blow away in the dust."

Source: Abel, 2016.

precautionary principle the view that policies should account for uncertainty by taking steps to avoid low-probability but catastrophic events.

good policies for resource management in national waters, these species can be harvested as an open-access global resource, which almost inevitably leads to stock declines. Only an international agreement can address an issue concerning global commons.

In 1995, the first such agreement was signed: the Convention on Highly Migratory and Straddling Stocks. This convention embodies a principle of ecological economics introduced in Chapter 9: the **precautionary principle**. This principle suggests that, rather than waiting until depletion is obvious, fishery access should be controlled before problems appear, with measures to limit the total catch rate, establish data collection and reporting systems, and minimize bycatch through the use of more selective gear.[18]

Demand-Side Issues: Changing Consumption Patterns

In addition to fishing industry regulations, altering demand patterns for fish and fish products can help achieve more sustainable outcomes. Public education campaigns that identify fish and seafood produced with environmentally-damaging techniques may lead consumers to avoid these species. For example, a boycott of swordfish aimed at stopping the decline of this species gained the support of numerous restaurant chefs and consumers. Web sites such as seafoodwatch.org provide consumer guides that indicate which species are sustainable choices, and which species should be avoided. In general, eating fish that are lower on the food chain reduces environmental impacts. Such "low trophic" species, including tilapia, catfish, and mollusks.[19]

ecolabeling a label on a good that provides information concerning the environmental impacts that resulted from the production of the good.

Ecolabeling, which identifies products produced in a sustainable manner, has the potential to encourage sustainable fishing techniques. Products of certifiably sustainable fishing practices can often command a slightly higher market price. By accepting this price premium, consumers implicitly agree to pay for something more than the fish they eat. They pay a little extra for the health of the ocean ecosystem and the hope of a supply of fish to feed people in the future as well as in the present. These consumer choices give the fishing industry a financial incentive to use sustainable methods.

In economic terminology, we can say that consumers who favor sustainable practices are internalizing the positive externalities associated with sustainable fishing techniques through their willingness to buy ecolabeled products. Governments or well-respected private agencies can oversee certification of sustainable fish products. A prominent example is "dolphin-safe" ecolabeling, which has been instrumental in reducing the number of dolphin killed as bycatch during tuna fishing.

About 20 percent of world fish production is used for nonfood uses, such as fishmeal and oils.[20] Alternative use of soymeal and other sources of protein in animal and fish feed would relieve pressure on fisheries and potentially make more fish available for direct human consumption. This would depend, of course, on increased output of land-grown protein products such as soybeans, which as we saw in Chapter 16 may pose other environmental issues.

Aquaculture: New Solutions, New Problems

People in developed countries currently consume 23 percent of the global fish catch; the other 76 percent is consumed in the developing world, where fish is an important protein source.[21]

Increasing population and income in developing countries will likely produce steady growth in global demand for fish and fish products, but supply expansion, at least from wild fisheries, appears to be close to its limits, as shown in Figure 18.5.

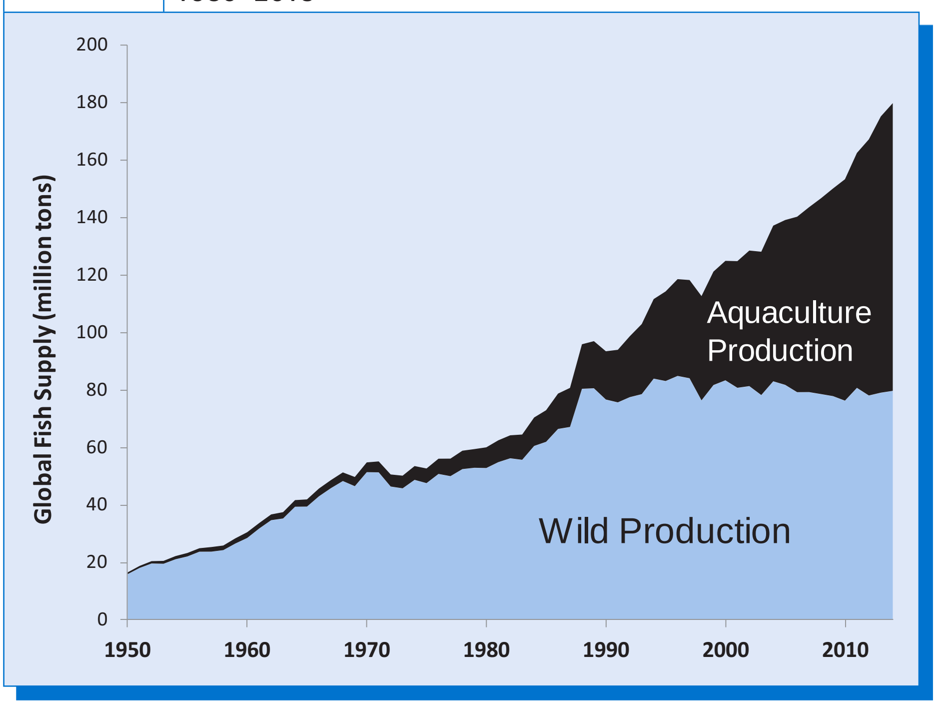
aquaculture the controlled cultivation of aquatic organisms, including fish and shellfish, for human use or consumption.

monoculture an agricultural system involving the growing of the same crop exclusively on a piece of land year after year.

As the global catch of wild marine fish has leveled off, an increasing percentage of the world's fish supply comes from **aquaculture**—fish farming, often in large offshore pens. Aquaculture is largely responsible for recent increases in world fish production (see Figure 18.7). In recent years the supply of fish from aquaculture has exceeded the supply from wild (or "capture") stocks. China is the world's largest producer of fish from aquaculture, accounting for 60 percent of global production. The expansion of aquaculture has allowed global per-capita fish consumption to increase steadily despite stable or declining wild catch. The growth of per-capita fish consumption has been most dramatic in developed countries, with consumption increasing from 5 to 19 kg per person per year from 1961 to 2013.[22]

But from an environmental point of view aquaculture may pose as many problems as it solves. While traditional aquaculture systems often raised several species of fish in ecologically healthy combination with crops and animals, modern systems often rely on a **monoculture** of economically profitable species such as salmon and shrimp. Such systems can have significant negative externalities. Excess food and fish waste contaminate the

Figure 18.7 Global Fish Harvest, Wild Catch and Aquaculture, 1950–2013



Sources: Food and Agriculture Organization of the United Nations (FAO), Global Capture Production Statistics; Global Aquaculture Production Statistics, accessed September 2016.

aquatic environment, and captive fish can spread disease to wild stocks or, if they escape, degrade the wild gene pool. Shrimp farms, which often replace mangrove forests, are especially ecologically destructive:

> In the short term, intensive shrimp farming is highly profitable: in a year, an individual shrimp farmer can make up to $10,000 per hectare for intensive production rates of 4 or 5 tons per hectare. This compares to the roughly $1,000 per hectare that a species such as milkfish or carp generates. But these economic returns do not account for ecological—and economic—losses such as habitat degradation. By converting diverse ecosystems to simple ones, fish farmers and the public lose a host of ecological goods such as fish, shellfish, timber, charcoal, and other products. They also lose services that coastal ecosystems provide, such as filtering and purifying water, cycling nutrients, removing contaminants and buffering the land from coastal storms and severe weather. A study of the Matang mangrove in Malaysia revealed that its value for coastal protection alone exceeded the value of farmed shrimp by 170 percent.[23]

As the global demand for fish continues to increase, along with stable or declining wild catch in the future, further growth in aquaculture production is projected. According to the World Resources Institute, aquaculture production will need to more than double by 2050 to meet growing demands driven by population growth and higher incomes.[24]

Box 18.2 SUSTAINABLE AQUACULTURE IN HONDURAS

Tilapia has become one of the top species of fish produced using aquaculture. Tilapia grow rapidly, tolerate high densities, and can be very profitable. But managed poorly, tilapia aquaculture can devastate a local ecosystem. One such example occurred in Lake Apoyo in Nicaragua. Some fish escaped from a tilapia farm operating in the lake in the 1990s. The non-native species quickly wiped out one of the lake's vital plant foods and the lake's ecosystem collapsed. The tilapia farm closed in 2000 after just five years, and the lake is still just beginning to recover.

But more recently, a tilapia farm in neighboring Honduras demonstrates that aquaculture can be managed for environmental sustainability. The Aquafinca farm continually monitors its waters to ensure that oxygen and nutrient levels remain acceptable. Tilapia are prevented from escaping into the surrounding waters by fish mesh cages. The farm's wastes are processed into fishmeal and fish oils. Martin Sukkel, chief operating officer of the farm, says that, "Our philosophy has always been to have a business that is sustainable for the long-term in an environmental and social sense. If we screw up the water, we're screwing up our own farming environment. If your horizon is five or ten years, you may not care—but we want to be here indefinitely."

Aquafinca aims to become to first tilapia farm to meet the Aquaculture Stewardship Council's (ASC) standards for sustainable aquaculture. Several other farmers have also expressed interest in complying with the ASC standards. But Sukkel is not merely seeking a competitive advantage over other farms, but planning for a long-term shift in the industry. He notes that, "ASC certification may be a competitive advantage for us for a few years, but it won't be in the long term, and we don't want it to be. Food safety standards aren't a competitive advantage—they're just a condition of doing business. Sustainability standards should be the same. Sustainability is not easy, and it looks expensive, but it's a very profitable investment if you're prepared to look long term."

Source: WWF, 2012.

In the last couple of decades, progress has been made to reduce the environmental impacts of aquaculture. For example, the Aquaculture Stewardship Council (ASC), co-founded by the environmental organization WWF, has developed standards for sustainable aquaculture, with a focus on shrimp and salmon farming. These standards are designed to limit the use of antibiotics, reduce pollution as a result of overfeeding, prevent the destruction of mangrove habitats, and keep surrounding waters clean. ASC guidelines also ensure that aquaculture workers are treated fairly and that indigenous rights are protected. By 2020 it is expected that 50 percent of global salmon aquaculture will meet ASC standards. For more on sustainable aquaculture, see Box 18.2.

Summary

A renewable natural resource system such as a fishery involves both economic and ecological principles. In a natural state, fish populations reach an equilibrium level based on the carrying capacity of the environment. Human exploitation of the resource can be sustainable provided that it is consistent with this natural carrying capacity.

Economic analysis of fisheries suggests that economically efficient resource use can be compatible with ecological sustainability. Setting annual harvest equal to natural growth, we can then identify an economically optimal equilibrium for the harvest level that maximizes net social benefit and is also ecologically sustainable. But open-access conditions, without harvest limits, create a strong tendency toward overexploitation in many fisheries and can even lead to the collapse of the fishery.

On a global scale, fishing fleet capacity has continued to increase, with the result that about 90 percent of the world's fisheries are classified as overfished or fully fished. In recent years, despite an increase in global fishing effort, wild catch levels are constant or declining. This suggests that current harvest levels are generally above the maximum sustainable yield, and that further expansion of fishing effort would only decrease yields more rapidly.

Policies for maintaining sustainable yield and rebuilding depleted fisheries can involve a combination of regulation and market mechanisms. International conventions have set guidelines for territorial rights and management practices. Countries can require fishing licenses or impose quotas to limit access to the fishery. Region-wide quotas can be difficult to enforce, but systems of individual transferable quotas have been successfully implemented.

Fish is an important protein source, especially in the developing world, where demand can be expected to grow as population and income rise. Consumption patterns can be modified to promote more sustainable fisheries management through consumer awareness and certification or ecolabeling programs. With global wild fish catch levels stable or declining, increasing fish demand will need to be met through expansion of aquaculture. Aquaculture has great potential but can also involve significant environmental costs. Recent efforts to reduce the environmental impacts of aquaculture show promise, but more progress is necessary.

Key Concepts

aquaculture

bycatch

carrying capacity

ecolabeling

economic optimum

Exclusive Economic Zone (EEZ)

fully fished

individual transferable quotas (ITQs)

inflection point
Law of the Sea
logistic curve
market failure
maximum sustainable yield (MSY)
monoculture
open-access resource
overfished
population biology
precautionary principle
renewable resources
resilience
sink function
source function
stable equilibrium
sustainable management
total product
tragedy of the commons
underfished
unstable equilibrium

Discussion Questions

1. What is the basic reason for depletion of fisheries? Which factors have made this problem especially severe in the modern period? How can this issue be related to the difference between economic and ecological analyses of a fishery?
2. What are the advantages and disadvantage of the following policies for fisheries management: private ownership, government regulation through licensing, the use of individual transferable quotas? In what circumstances might each one be appropriate?
3. Explain the interrelationship between the following concepts as they relate to fisheries: scarcity rent, maximum sustainable yield, economic efficiency, ecological sustainability. How should these concepts be used to guide fisheries management policies?

Exercise

Suppose that a fishery is characterized by the following relationship between total fish stock and annual growth (ignore the third column for now):

Stock (thousand tons biomass)	Annual Growth (tons)	Number of Boat Trips Required to Catch Annual Growth
10	0	–
20	800	2,300
30	1,600	2,200
40	2,300	2,100
50	2,800	2,000
60	3,100	1,600
70	3,200	1,300
80	3,000	1,000
90	2,700	800
100	2,300	600

110	1,800	400
120	1,200	200
130	500	100
140	0	0

a) First, construct a graph showing the relationship between stock and growth, similar to Figure 18.2. Identify on your graph the stock levels that correspond to the maximum sustainable yield, and the stable and unstable equilibrium stock levels for this fish population in a natural state.

b) Next, present a table showing the population growth rate, expressed as a percentage, at each stock level. For example, with a stock of 50,000 tons the annual growth is 2,800 tons, or 5.6 percent. What stock level maximizes the population growth rate? What point in Figure 18.1 does this growth rate correspond to (A, B, C, or D)?

c) Suppose you are a resource manager overseeing this fishery. You want to ensure the ecological sustainability of the fishery by requiring that annual harvest should equal annual natural growth. You have collected data on the number of boat trips required to catch the annual growth of fish at different population stocks. This is given in the third column in the table above, which can be read from bottom to top to show increasing fishing effort. Assume that it costs $1,000 to operate a boat trip and that fish sells for $1,000 per ton.

You must determine the annual quota for fish catch (in tons) and the population level you wish to maintain. What level of fishing effort maximizes economic efficiency while still being ecologically sustainable? Show your work. (Hint: Calculate industry revenues, costs, and profits for each level of fishing effort from 0 to 2,300.) Present a graph similar to Figure 18.3 showing total revenues and total costs to support your answer.

Notes

1. FAO, 2016a.
2. FAO, 2016b.
3. http://www.usatoday.com/pages/interactives/groundwater/.
4. A logistic curve is an S-shaped growth curve that tends toward an upper limit. For an exposition of the mathematical analysis of logistic growth, see Hartwick and Olewiler, 1998, Chapter 4.
5. At an inflection point, the curvature of the line changes from positive (upward) to negative (downward). In the terminology of calculus, the second derivative goes from positive to negative and equals zero at the inflection point.
6. For an advanced treatment of the dynamics of fisheries, see Clark, 1990.
7. At this point, the slopes of the two curves are equal. Note that we could also solve for the economic optimum using marginal analysis, as we did in Chapter 4.
8. The levels of fishing engaged in by Native American tribes before European colonization would have had little impact on the natural equilibrium.
9. Watson *et al.*, 2012.
10. World Bank and FAO, 2009, p. xviii.
11. The classification scheme, devised by the UN Food and Agriculture Organization, also considers spawning potential, size and age composition, and stock abundance. See FAO, 2012b.
12. Freitas *et al.*, 2008, Introduction.

13. Davies *et al.*, 2009, pp. 669–670.
14. See Hagler, 1995; Ogden, 2001.
15. World Bank and FAO, 2009, p. xxi.
16. For a survey of the effects of entry restrictions in fisheries, see Townsend, 1990.
17. See Arnason, 1993; Duncan, 1995; Young, 1999.
18. McGinn, 1998.
19. http://www.wri.org/blog/2014/06/sustainable-fish-farming-5-strategies-get-aquaculture-growth-right.
20. FAO, 2012a.
21. FAO, 2016b.
22. Ibid.
23. McGinn, 1998, pp. 48–49.
24. http://www.wri.org/blog/2014/06/sustainable-fish-farming-5-strategies-get-aquaculture-growth-right.

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Web Sites

1. **www.fao.org/fisheries/en/.** The Food and Agriculture Organization's main fisheries webpage. It includes links to their biennial "State of World Fisheries and Aquaculture" report, which contains detailed data on fish production and consumption.
2. **www.worldbank.org/en/topic/environment/brief/global-program-on-fisheries-profish.** The World Bank's Global Program on Fisheries (PROFISH) webpage. It includes links to various publications and projects.
3. **http://oceana.org/.** Web site of Oceana, the "largest international organization focused solely on ocean conservation." The site describes various ocean conservation projects that Oceana is working on, as well as links to publications.

CHAPTER 19

Ecosystem Management: Forests

Chapter 19 Focus Questions

- What are the economic and ecological principles of forest management?
- What are the causes of forest loss, and what regions of the world are losing or gaining forest cover?
- How can policies for sustainable forestry be implemented?

19.1 THE ECONOMICS OF FOREST MANAGEMENT

Forests, like fisheries, are primarily biological systems. When we exploit them for human use, both ecological and economic analyses can help us understand principles of effective management. As with fisheries, the natural growth rate is fundamental in forest ecology and provides a link between ecological and economic analyses. An important factor in forest management policy is the cumulative nature of forest growth: biomass accumulated over years, decades, or even centuries will remain available if left undisturbed—either for human use at a later time, or to fulfill functions such as carbon storage, water retention, and maintenance of biological diversity. Thus, choices about the time of harvesting, as well as both economic and ecological considerations, are important in forest management.

If we measure the volume of standing timber in a forest over time, we obtain a **logistic curve** similar to that for the growth of a fishery (Figure 19.1).[1] However, the logic of harvesting is somewhat different for forests than fisheries. From an economic point of view, we can see a standing forest as an **asset**, or **stock**, that can also yield a **flow** of economic value to humans. If a forest is privately owned, the owner will balance the asset value against the stream of income available from use. A simplified example will demonstrate the economic principle involved. Initially, we assume that the only financial value of the forest to the owner is as a source of timber.

Consider a forest with 100,000 tons of standing timber and a growth rate of 5,000 tons of additional biomass per year. At a price of \$100 per ton, the value of the forest if it is **clear-cut** (logged all at one time) is \$10 million. The alternative is a policy of **sustainable management**, in which the annual harvest is no more than the annual growth. This approach would yield \$500,000 per year.

Which is economically preferable? It depends on the **discount rate** used to determine the present value (PV) of the sustainable management alternative. If we assume that sustainable management will provide the same annual income of \$X (\$500,000 in our example) indefinitely, we can calculate the PV using the formula:[2]

$$PV = \sum_{i=1}^{\infty} \$X / \left(1+r\right)^{i} = \$X / r.$$

So, at a discount rate of 4 percent, the PV of the sustainable yield alternative is:

$$PV = \$500{,}000/0.04 = \$12.5 \text{ million}.$$

And at a discount rate of 6 percent, the PV would be:

$$PV = \$500{,}000/0.06 = \$8.33 \text{ million}.$$

logistic curve/logistic growth an S-shaped growth curve tending toward an upper limit.

assets something with market value, including financial assets, physical assets, and natural assets.

stock the quantity of a variable at a given point in time, such as the amount of water in a lake, or the amount of timber in a forest, at a given time.

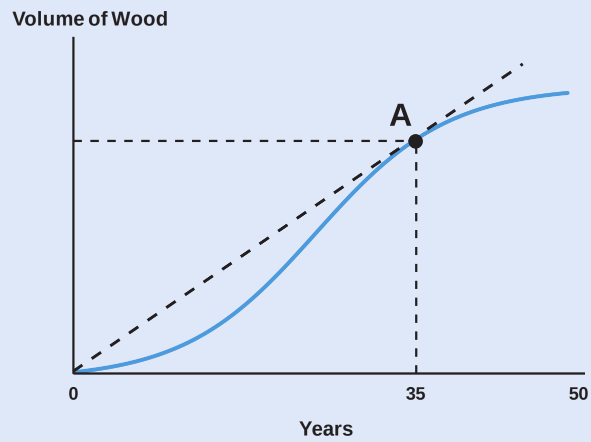
flow the quantity of a variable measured over a period of time, including physical flows, such as the flow of a river past a given point measured in cubic feet per second, or financial flows, such as income over a period of time.

clear-cut the process of harvesting all trees within a given area.

sustainable (natural resource) management management of natural resources such that natural capital remains constant over time, including maintenance of both stocks and flows.

discount rate the annual rate at which future benefits or costs are discounted relative to current benefits or costs.

Figure 19.1 Forest Growth over Time



As the discount rate increases, the PV of the sustainable management alternative is reduced. Comparing these figures with the $10 million present value of an immediate clear-cut, we find that at a 4 percent discount rate, sustainable management is economically preferable, but at the higher 6 percent rate the owner will do better with a clear-cut.

Another way of seeing this is to note that from the owner's point of view, the clear-cut revenue of $10 million can be invested at 6 percent to earn $600,000 per year, a more lucrative option than the $500,000 from sustainable management. Thus a financial variable, the commercial rate of interest, will significantly influence private forest management policy. Privately-owned forests with a growth rate below the going rate of interest are likely to be harvested as fast as possible. U.S. corporate forest management frequently applies this logic, especially when forest owners have high-interest debt to pay off.

This simple example fails to consider forest replanting and regrowth. We can apply a more sophisticated version to determine the economically-optimal harvesting period (the number of years from planting to cutting).

Consider a forest's biological growth pattern. Figure 19.1 shows that a relatively young forest grows more rapidly than a mature forest. The **mean annual increment (MAI)**, or average growth rate, is obtained by dividing the total **biomass**, or weight of timber, by the age of the forest. Graphically, the MAI at any point on the growth curve is defined by the slope of a straight line from the origin to that point. The maximum MAI occurs where a line from the origin is exactly tangent to the curve (point A in Figure 19.1).

One possible rule for harvesting would be to clear-cut the forest at a period that maximized the MAI (35 years in Figure 19.1). This would result in the highest total volume of timber and highest average annual revenues over time, assuming a constant price for timber.

To find an economic optimum, however, we must consider two other factors. The first is the cost of harvesting—the labor, machinery, and energy required to cut the timber and transport it to market. The second factor, as our earlier example showed, is the discount rate. Both revenues and costs must be discounted to calculate the present value of various harvesting policies.

mean annual increment (MAI) the average growth rate of a forest; obtained by dividing the total weight of timber by the age of the forest.

biomass an energy supply from wood, plant, and animal waste.

To determine the economic optimum, we first obtain the total revenue (TR) and total cost (TC) for harvesting different quantities of timber, as shown in Figure 19.2. Total revenue is simply the volume of timber (from Figure 19.1) multiplied by the per-unit price. Thus the shape of the TR curve reflects the shape of the growth curve from Figure 19.1. Note that total cost is initially higher than total revenue because of fixed costs such as machinery. Costs then rise over time in rough proportion to the amount of timber harvested, and would also include the cost of replanting. Total revenue minus total cost (TR − TC) indicates the profit from harvesting at some future point.

Next, profits expected at a future time must be discounted to calculate their present value. The point at which the discounted value of (TR − TC) is maximized gives the **optimal rotation period** for harvesting, from the point of view of economic profitability. This is shown in Figure 19.3. If profits are not discounted (r = 0), then the economically-optimal rotation period is a little more than 45 years based on this example. With a 2 percent discount rate, the optimal rotation period falls to around 37 years. With a higher discount rate of 5 percent, the optimal rotation period drops to 30 years.[3]

optimum rotation period the rotation period for a renewable resource that maximizes the financial gain from harvest; determined by maximizing the discounted difference between total revenues and total costs.

At higher discount rates, the present value of expected future income shrinks. Thus the higher the discount rate, the shorter will be the optimal harvesting period. This example helps to explain why plantation forestry is generally based on faster-growing softwood trees. Slower-growing hardwoods or mixed forest might be profitable over the long term, but at a commercial rate of discount the present value of slower-growing trees will be too low to be attractive to timber companies. The determination of commercial interest rates depends on financial factors unrelated to ecological systems, but interest rates can have significant impact on forest management.

This economic logic also helps explain pressure on old-growth forests. Standing forests that may have taken hundreds of years to grow represent an economic asset that can be harvested for immediate profit. Replanting tends to be in faster-growing species. Although replanting an entire forest with a single fast-growing species or an agricultural crop represents a significant ecological loss, commercially speaking it may be the most profitable option.

Figure 19.2 Timber Total Revenues and Costs over Time

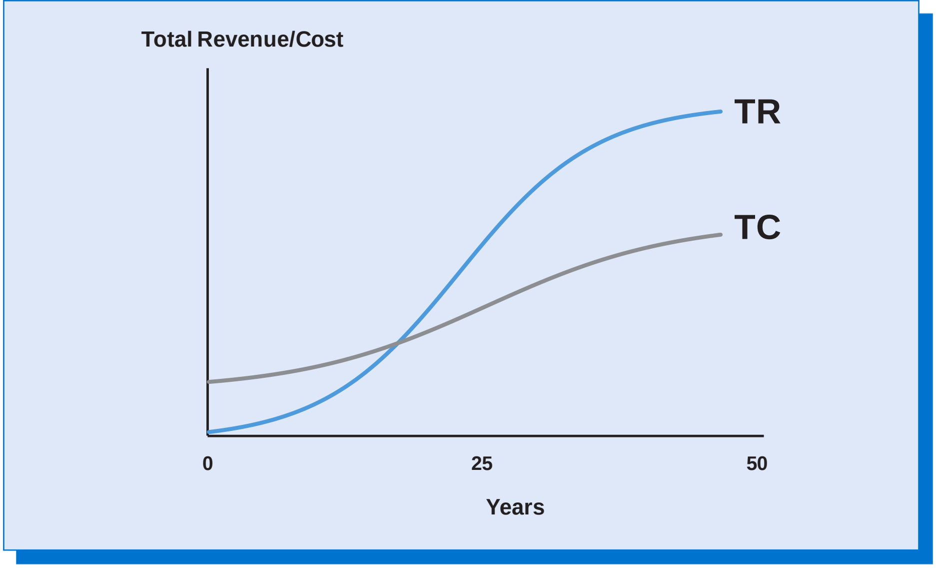
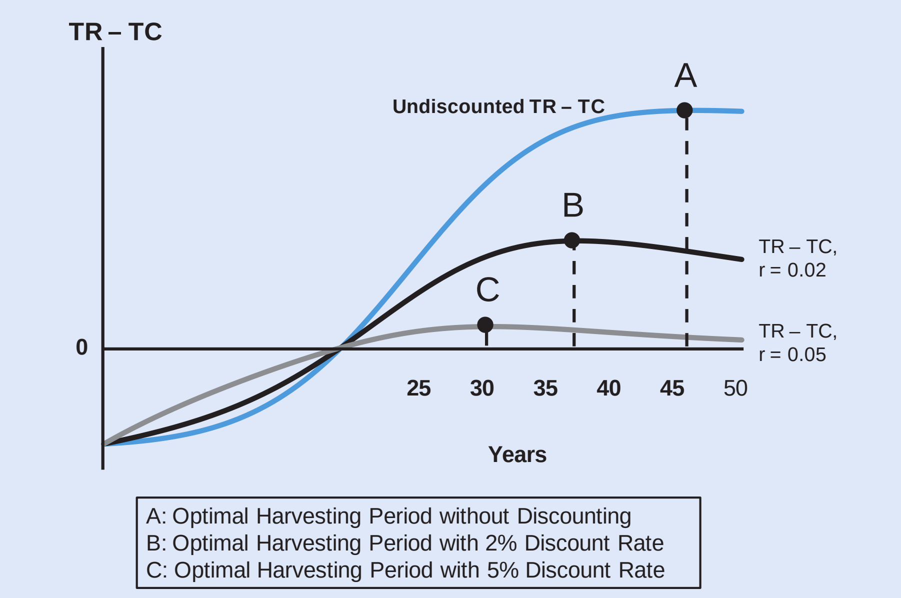


Figure 19.3 Optimum Harvest Period with Discounting



Box 19.1

DEFORESTATION IN SOUTH AMERICA

The Chaco forest, covering parts of Paraguay, Argentina, Bolivia, and Brazil, is considered Latin America's second-most important forest behind the Amazon. Covering an expanse of territory about the size of Poland, much of the Chaco has remained impenetrable for centuries, protecting its ecological and cultural resources. But now huge tracts are being razed in a scramble to convert the land for ranching and farming. "Paraguay already has the sad distinction of being a deforestation champion," says José Luis Casaccia, a former environment minister. Much of the Chaco forest in eastern Paraguay has already been cleared for soybean farms; little more than 10 percent of the original forest remains. So much land is being bulldozed and so many trees are being burned that the sky sometimes turns "twilight gray" in the daytime. "If we continue with this insanity," says Casaccia, "nearly all of the Chaco's forests could be destroyed within 30 years."

The soybeans from the region are mostly exported to provide animal feed. University of Illinois economist Mary Paula notes, "Without a doubt, demand for soybeans will continue to grow because of the growing middle classes in countries like China, Brazil, Russia, and India where people are eating more meat." Global production of soybeans has increased from less than 30 million metric tons in the 1960s to around 300 million metric tons.

Large American agricultural companies including Cargill and Archer Daniels Midland purchase much of the soybeans from the Chaco, further processing it into feed or other food sources. The presence of these large buyers has been transforming farming in the region, encouraging industrial-scale farming with little concern for biodiversity. Environmental groups, including the WWF, are pressuring the American companies to agree to conservation guidelines as soybean production in the region continues to expand, with an emphasis on protecting the remaining ecologically-sensitive areas.

Sources: Romero, 2012; MacDonald, 2014.

The principles of commercial forest management can thus often conflict with ecological goals. Although it may be possible to internalize some of the social costs and benefits related to forest management, for vast areas of privately owned or open-access forest, market profitability is the overriding management principle. This is one of the factors that has led to serious problems of forest and **biodiversity** loss throughout the world (see Box 19.1).

biodiversity (biological diversity) the maintenance of many different interrelated species in an ecological community.

Clear-cut logging and conversion to agriculture often prove more profitable than sustainable forest management. But sustainable management likely provides greater non-market benefits, including greater biodiversity and recreational opportunities.[4] Thus our economic calculations might be altered by considering the positive externalities associated with forest conservation—values which are generally not reflected in the market.

19.2 FOREST LOSS AND BIODIVERSITY

Human activity has reduced forest area in some cases and increased it in others, as well as changing forest biodiversity. Worldwide, about two-thirds of tropical deforestation results from conversion of land for agriculture rather than directly from timbering. Typically, though, opening up forest areas with logging roads often allows access and encourages destructive agricultural techniques.

As human populations have increased, natural forests have typically been cut down and at a later stage replaced with planted forests. This gives rise to a U-shaped curve showing the change in total forested area over time as population increases and economic development proceeds (Figure 19.4). Most tropical areas of the world are still on the downward-sloping portion of this curve, suffering net forest loss. Many temperate zones have a stable or increasing forest area, having eliminated most of their natural forest and replaced it with planted or second-growth forest.[5]

Considering all types of forests, the rate of net global deforestation was reduced by about 50 percent between 1990 and 2015.[6] But this still means the world is losing about 3 million hectares of forest per year, an area equivalent to the U.S. state of Maryland. Some forest types

Figure 19.4 Deforestation and Tree Cover

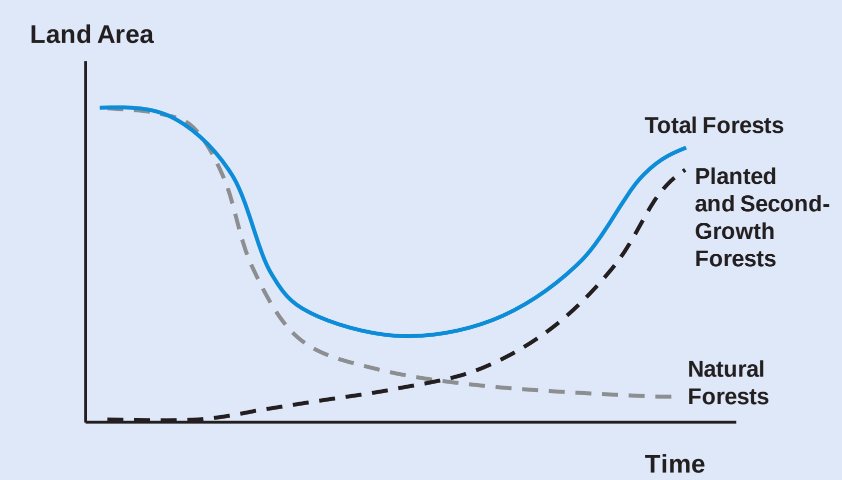
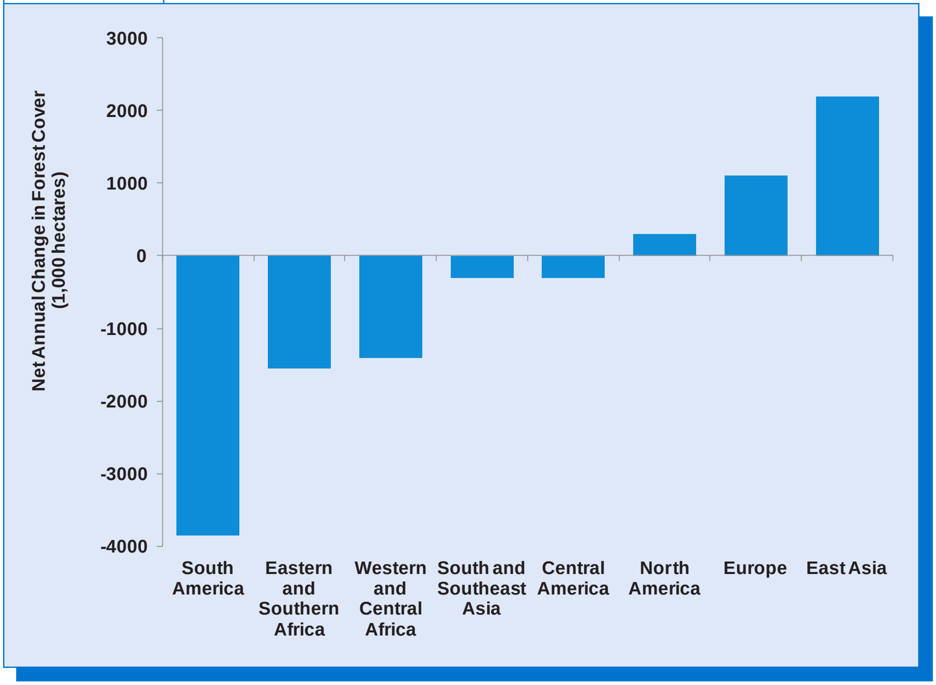


Figure 19.5 Net Change in Total Forest Area, by Region, 2000–2010



Source: FAO, 2016.

are actually increasing in area, mainly concurrent with a reduction in agricultural land. Boreal forests (coniferous trees in cold regions) and temperate forests (in regions with mild winters and moderate rainfall) are generally stable or increasing. Tropical forests, where biodiversity tends to be greatest, are declining in most areas. Figure 19.5 shows the net change in total forest area over 2000–2010 by region. Total forest loss is greatest in South America, with significant forest losses also occurring in Africa. Net forest area is increasing in North America, Europe, and East Asia (see Box 19.2 on China's recent efforts to increase forest cover).

According to the Food and Agriculture Organization (FAO), the rate of global tropical deforestation has been declining.[7] But a more detailed analysis of tropical forests in 2015 indicates that the rate of tropical deforestation is increasing. Using high-resolution satellite maps, the study found, "a 62% acceleration in net deforestation in the humid tropics from the 1990s to the 2000s, contradicting a 25% reduction reported by the United Nations Food and Agriculture Organization."[8] The increase in deforestation was greatest in Latin America, dominated by Brazil, and Asia. But the study did find that deforestation peaked during 2000–2005, and declined during 2005–2010.

Conversion of forests to agriculture, ranching, or pasture is the primary cause of forest loss throughout the developing world (Figure 19.6). In Latin America, the main driver is conversion of forest land for ranching or pasture, while in Southeast Asia and Africa it is agriculture, with commercial agriculture more significant in Southeast Asia and subsistence agriculture the main driver in Africa.

> **monoculture** an agricultural system involving the growing of the same crop exclusively on a piece of land year after year.

Even in areas where forest area is stable or increasing, the threat to biodiversity from economic uses of forests may still be great. Cultivated forests tend to be **monocultures**—huge stands planted with a single species selected for maximum economic return. Such artificial forests

Box 19.2
REFORESTATION IN CHINA

China has long suffered from severe problems of soil erosion and flooding due to loss of forest cover. After significant flooding in 1998, China embarked on the largest reforestation project in the world. The national government instituted several programs to increase forest cover. The Grain to Green program focused on converting agricultural fields on steep slopes back to forests. Volunteers participating in a national tree-planting movement throughout the country have planted over 35 billion trees. A forest conservation program instituted logging bans in many areas, and also paid rural households to follow conservation practices.

A 2016 analysis indicates that China's efforts have been a success in many respects. Total forest cover in China has expanded, which has increased carbon storage—thus slowing the accumulation of carbon in the atmosphere and mitigating climate change. But lead author of the study, Andrés Viña, notes that a more comprehensive perspective suggests that the news is not all positive. He says that, "China has become one of the leading timber importers in the world. It's Southeast Asia, Vietnam, Indonesia, as well as Africa, northern Eurasia, Russia are the ones that are now supplying [China's timber, largely offsetting the forest gains within China]. In a sense, the program exported the deforestation."

Viña also believes that China's shift from domestic timber production to importing timber has had a net negative effect on biodiversity. This is because China's reforestation is generally occurring in areas with low biodiversity, but deforestation in countries that are supplying China with timber is occurring in areas with high biodiversity. So while the program appears to be a clear success within China, its overall effect in terms of biodiversity and climate is less obvious. Recent analyses also indicate that a large portion of China's gains are better classified as shrub-land rather than as mature forest.

Sources: "Afforestation," *China Through a Lens*, www.china.org.cn/english/features/38276.htm; Shockman, 2016; Mike Ives, "Trees or Shrubs: Study Disputes Success of China's $100 Billion Forest Effort," *New York Times*, May 3, 2017.

displace natural forests, which provide habitat for many more species. Over a long period of time, it is possible to regenerate diverse forests, but economic incentives to manage forests for diversity are often lacking.

Managing forests for the maximum sustainable yield may not be compatible with ecosystem sustainability. Forest managers can maintain sustainable yield merely by replanting all logged areas with a single species of fast-growing tree. This offers sustainable flows of timber and income for the forest owner but destroys the original complexity of the forest ecosystem, to the detriment of many animals and plants that thrive in a multispecies forest.

The principle of **resilience** is central to ecosystem sustainability.[9] Resilience is a "bounce-back" capacity: the ability of an ecosystem to recover from disruption (e.g., a forest fire or pest infestation). In general, complex ecosystems display more resilience than simple systems. If a plantation forest contains only one species of tree, an attack by a single pest may destroy the entire forest. A forest with many species is much more likely to withstand pest attacks. The proportion of species within the forest may change, but its ecological integrity and health will survive.

> **resilience** the capacity of ecosystem to recover from adverse impacts.

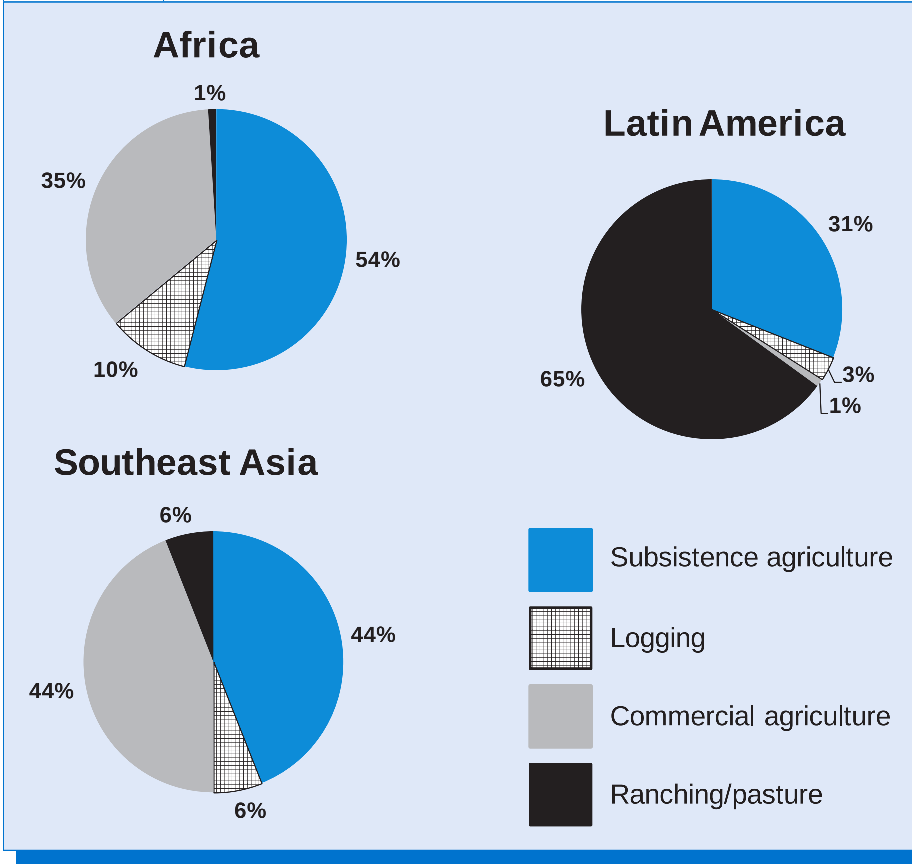
Deforestation is a particular threat to biodiversity in tropical forests, as about 80 percent of the documented species on the planet are found in these forests.[10] Thus the overall level of global biodiversity is closely linked to the health of rainforests. Many ecologists warn that we are in the midst of an extinction crisis, driven largely as a result of habitat loss and degradation. A 2015 analysis of global biodiversity concludes:

> The evidence is incontrovertible that recent extinction rates are unprecedented in human history and highly unusual in Earth's history. Our analysis emphasizes that our global society has started to destroy species of other organisms at an accelerating rate, initiating a mass extinction episode unparalleled for 65 million years. If the currently elevated extinction pace is allowed to continue, humans will soon (in as little as three human lifetimes) be deprived of many biodiversity benefits. [Preventing a] mass extinction will require rapid, greatly intensified efforts to conserve already threatened species and to alleviate pressures on their populations—notably habitat loss, overexploitation for economic gain, and climate change.[11]

According to one measure of global biodiversity—the Living Planet Index developed by the World Wide Fund for Nature (WFF)—vertebrate populations have declined by an average of more than 50 percent since 1970. The decline has been higher in tropical, as opposed to temperate, regions. Latin America has seen the greatest decline in vertebrate populations, with an 83 percent drop.[12]

A detailed study of the Brazilian Amazon in 2015 concluded that biodiversity was significantly reduced in areas that had been converted from forests to agriculture and ranching. However, the analysis found that with careful management, biodiversity could be largely

Figure 19.6 Regional Breakdown of Drivers of Deforestation



Source: Project Catalyst, 2009.

retained even as some areas were deforested. The key is to establish a widespread network of diverse and interconnected forest reserves, which is more effective than protecting just a few, but larger, reserves. Even when forests have been disturbed from past activities, the network reserve strategy could support up to 80 percent of the biodiversity of pristine forests.[13]

19.3 POLICIES FOR SUSTAINABLE FOREST MANAGEMENT

The economic forces that promote forest destruction operate on multiple levels, from the global to the local. Taking the broadest perspective, we observe a steadily increasing global market for wood products, meat, and agricultural crops, leading to declining natural forest area with conversion to ecologically less desirable monocultures. With global markets, economic forces can shift deforestation from region to region. According to a 2011 report:

> reductions in deforestation in one area, by limiting supply and raising prices, can increase the pressure for deforestation elsewhere. Sometimes the same companies—e.g., multinational timber companies—can actually move from one place to another; but even without this, the demand for deforestation will be displaced (or "leak") to other places due simply to the operation of the global market. Like a balloon that is squeezed on one end, there will always be pressure for it to push out at the other end. . . . [I]n a globalized world, it always must be assumed that the drivers of deforestation are mobile and the forces of the market will move them around the world.[14]

As we also saw in Box 19.2, this suggests the need for a coordinated international response, rather than isolated national approaches. The United Nations has established the Forum on Forests (UNFF) in 2000, to promote, "the management, conservation, and sustainable development of all types of forests and to strengthen long-term political commitment to this end."[15] The UNFF prepared forestry guidelines in 2007, with four global objectives:

1. Reverse the loss of forests through sustainable forest management;
2. Enhance the economic, social, and environmental benefits of forests, and improve the lives of people that depend on forests;
3. Significantly increase the area of protected forests;
4. Increase the financial resources, including international developed aid, devoted toward sustainable forest management.[16]

The UNFF guidelines, however, are non-binding and voluntary. While a legally-binding international forest agreement could ensure more sustainable management of the world's forests, major forestry nations, including the United States, Brazil, and Russia, have resisted a strong international agreement, arguing that individual nations should retain sovereignty over their own forests.[17]

Perhaps the greatest possibility for promoting sustainable forestry at the international level may be through agreements related to climate change. Forests play a critical role in climate change as they store significant quantities of carbon dioxide, the primary greenhouse gas. When forests are destroyed this stored carbon is released into the atmosphere. Deforestation accounts for about 15 percent of global carbon emissions, more than the total emissions from the world's cars and trucks.[18] According to a 2016 analysis, effective global forest management could provide about 20–40 percent of the total greenhouse gas reduction required to meet the UN's climate goal of a maximum 2ºC temperature increase relative to pre-industrial levels. Further, forests can store carbon at a much lower cost than trying to capture the carbon generated by electricity production from fossil fuels.[19]

Since the mid-2000s the United Nations has been negotiating a mechanism to integrate climate policy with sustainable forestry. The current approach, known as REDD+ (which stands for "reducing emissions from deforestation and forest degradation"), provides countries with credit toward climate mitigation targets with effective forest management.[20] For more on the role of REDD+ in relation to the 2015 Paris climate agreement, see Box 19.3.

At the national level, forest management varies significantly across countries. Weak forest policies are often a result of economic pressures. Governments often grant logging concessions and sometimes monopolies to timber companies. They have also encouraged large agricultural firms to encroach on the forest for extensive cattle ranching (Brazil and Central America) or cash-crop cultivation of coffee, tobacco, and other tropical crops (Indonesia, other Asian countries, and Latin America). Population increase also contributes to forest loss. Governments have encouraged settlements in formerly undisturbed forest areas to reduce pressure in heavily populated places.

Box 19.3
REDD+ AND THE PARIS CLIMATE AGREEMENT

The United Nations notes that limiting climate change to acceptable levels will be impossible without reducing carbon emissions from forests. The UN's REDD+ mechanism, established in 2008, provides financial incentives to developing countries in exchange for reducing their forest emissions and pursuing low-carbon development strategies. As of 2016 the REDD+ program was working with 64 developing countries, with most of the funding so far being used to establish an institutional framework for future forestry projects. For example, about $250,000 was provided to Malawi in 2014 to determine how the REDD+ program will integrate within the existing legal and policy framework, and to establish a roadmap for reaching out to stakeholders and encouraging participation in future projects. Papua New Guinea received $1.4 million to establish a forest monitoring facility, including training of staff.[21] A recent study indicates the potential for REDD+ to help preserve mangrove forests in Malaysia.[22]

These efforts will need to be scaled up significantly to have a measurable impact on limiting climate change. The inclusion of REDD+ in the 2015 Paris Climate Agreement is widely considered to be a significant breakthrough, with Article 5 calling for "policy approaches and positive incentives for activities relating to reducing emissions from deforestation and forest degradation, and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries."[23] At the Paris meeting several countries, including Germany, Norway, and the United Kingdom, pledged to increase their funding for sustainable forestry projects in developing countries. The developed countries have set a target of $1 billion of funding annually for REDD+ projects by 2020.[24] According to the World Resources Institute:

> Now that the new Agreement explicitly endorses REDD+, the future is brighter for forests and their contribution to climate mitigation. New funding is coming in, the guidelines are clear, and governments and the scientific community are slowly closing the data gaps that have presented hurdles in the past. Countries finally have the resources they need to ramp up action on forests, which will be critical to achieve the goal set in the Paris Agreement of getting to net-zero emissions in the second half of this century.[25]

Despite these pressures, some countries stand out for their efforts to foster improved forest practices. By 1990 Vietnam had lost over a third of its natural forests and the overall health of its forests was rapidly declining. To halt deforestation, in 1992 the country reduced allowable timber harvests, and banned the export of raw wood. In 1993 logging was banned in all protected areas, and a 30-year moratorium was instituted on logging in numerous important watersheds. These policies, along with reforestation efforts, have produced a dramatic turnaround. By the mid-2000s forest cover in Vietnam had increased more than 40 percent relative to its lowest level in the 1990s. The Vietnam Forestry Development Strategy calls for further increases in forest cover, promotion of eco-tourism, and that at least 30 percent of production forests will be certified sustainable by 2020. However, Vietnam has become more dependent on imported timber, and this partially offsets the progress made within the country.[26]

Costa Rica was once one of the most deforested countries in the world, but now it is widely recognized for its sustainable forest policies. Deforestation was driven by poor policies that promoted conversion of forests to pasture for cattle and a rapid expansion of the road system. In addition to setting aside forest reserves (over 25 percent of the land area of Costa Rica is protected), the country relies on economic policies to encourage forest protection. Costa Rica has one of the most comprehensive **payments for ecosystem services (PES)** policies to protect biodiversity and forest resources, instituted in the 1990s. As discussed in Chapter 9, PES programs provide compensation to natural resource owners in exchange for sustainable management. PES can effectively internalize positive externalities and alter forest management practices in favor of conservation.[27] Landowners in Costa Rica sign five-year contracts that commit them to maintain or expand forest cover on their lands. They are paid approximately \$200–\$500 per hectare, with annual disbursements, for fulfilling the conditions of their contracts. Between 1997 and 2008 over 6,000 contracts were signed, protecting about 500,000 hectares of forest. The funding for the PES program comes largely from taxes on timber and gasoline, along with contributions from the private sector and international organizations. As a result of the PES program and other policies, forest area in Costa Rica is now more than 50 percent of the total land area of the country, up from 25 percent in 1995.[28]

payments for ecosystem services (PES) payments provided to natural resource owners in exchange for sustainable management practices.

Recent efforts to promote sustainable forestry also focus on local management. In many cases, indigenous communities have traditionally managed forests in a sustainable manner, based on accumulated local knowledge. National policies that set aside protected reserves can be disruptive to local communities when traditional practices such as harvesting forest products are banned in protected areas. A multi-tiered approach instead designates different levels of protection to take account of the rights of indigenous peoples. Moving outward from a core highly-protected area, buffer zones are established in consultation with local people which permit small-scale sustainable economic development. For example, the Lacandona forest in Mexico, the largest tropical forest in the country, includes buffer zones that support more than 6,000 indigenous people practicing agriculture and other activities.[29]

In addition to thinking of forest policies at different geographical levels, we can also differentiate between policies implemented on the supply side to promote sustainable forestry, and policies on the demand side that aim to change consumption patterns, reduce waste, and expand recycling. We now consider each of these approaches.

Supply Side: Property Rights and Pricing Policies

One major issue in forest management throughout the developing world is the need for **secure property rights**. Individuals and communities whose land tenure is insecure, including many migrants, have little incentive to conserve forests. Economic necessity forces them

secure property rights clearly defined and legally binding rights of property ownership.

to exploit the forest for maximum short-term gain and then move on. If granted secure tenure, they will have an interest in a continuing flow of income from the forest, including forest products other than timber, such as fruits, latex (from rubber-tapping), or shade-grown coffee.[30]

Stable communities also have incentives to maintain forests in order to enjoy their accompanying positive externalities. A village or community situated in the mountains, for example, may undertake a program of reforestation both to sustain the supply of wood and because trees retain soil on the slopes, preventing erosion. Forested ecosystems also help to provide a stable supply of fresh water and prevent flooding.

Some positive externalities associated with forest maintenance or reforestation are global in nature. As mentioned above, forests remove and store atmospheric carbon, lowering the risks of global climate change. This may bring no immediate benefit to the local community, but future global climate change agreements may well provide compensation to countries that preserve or expand their forest cover. In the future, a country might be able to earn income from its forests by keeping them in place rather than by cutting them down for timber export. The carbon storage function of tropical forests has been estimated at $3.7 trillion, assuming a carbon storage value of $20 per ton.[31]

Another critical issue concerns access to public forest resources by private entities. While companies normally pay the government royalties for access to timber and other forest resources on public lands, these fees typically fail to provide adequate compensation to society for the loss of these resources. In addition to public financial costs, such as administration and road building, there are non-market costs such as reduced recreation values, habitat loss, carbon emissions, and water quality degradation. For example, a 2016 analysis of timber sales on public lands in Oregon found that the revenues from these sales only cover about 2 percent of the total economic costs of the lost resources.[32] Government policies of low-cost timber sales essentially constitute a subsidy to logging companies, as well as an inducement to corrupt practices, such as payoffs to government officials for valuable concessions. Since overexploitation of forests, as we have seen, has many negative externalities, this is a particularly inappropriate use of a subsidy, which economic theory tells us should be used only where clear positive externalities exist.

total economic value the value of a resource considering both use and nonuse values.

As we saw in Chapter 6 and many other instances throughout the text, the price of any natural resource should reflect its **total economic value**, considering both market and non-market values. Ecological values of forests include provision of water services and maintenance of water quality, carbon sequestration value, biodiversity value, recreation, tourism, and cultural values. Thus the total economic value of forests can considerably exceed the value of timber and other commercial products.

Numerous economic studies demonstrate that focusing on the financial value of timber to guide forest management can lead to inefficient use of forest resources. A 2013 study of forests in Tunisia found that the economic value of wood products represented only 5 percent of forests' total economic value, with the benefits from biodiversity and watershed protection exceeding the value of timber.[33] Similar results were obtained in a 2013 analysis of forests in Italy. Wood production only accounted for 4 percent of the total economic value, with higher values from recreation, climate regulation, and water quality protection, and non-use values.[34]

Economic theory supports secure property rights and full pricing of resources. But the ecological perspective adds another important dimension to forest management issues. Forests have to be seen as complex ecosystems to be managed, both to preserve healthy ecosystems and to supply of a wide array of goods and services for current and future generations. These ecological goals will often differ from the priorities of private landowners, who will seek to manage the forest for profitability, often selecting faster-growing species and cutting timber on a short cycle rather than allowing a mature forest to develop.

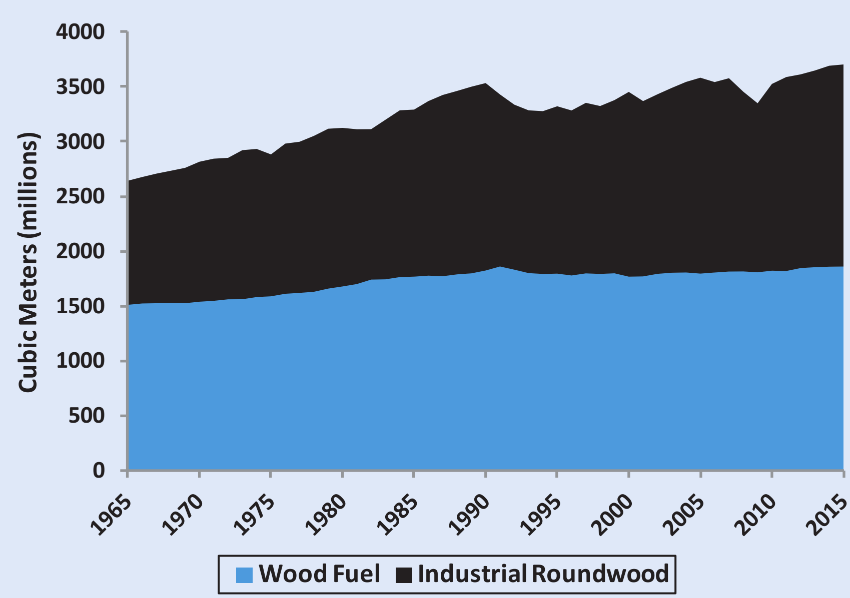
certification the process of certifying products that meet certain standards, such as certifying produce grown using organic farming techniques.

Government policy can encourage sound forest management by such measures as tax breaks for sustainable forestry or limitations on clear-cutting. From an economic theory perspective, the positive externalities associated with good forest management justify such policies. Programs have also begun for **certification** of sustainably produced wood so that consumers and public agencies can encourage sound practices by their purchasing choices. Experience shows that many consumers are willing to pay a premium above market price for sustainably produced wood. In 2016, the Forest Stewardship Council (FSC) identified 190 million acres of certified forest in 82 countries. However, 84 percent of FSC's certified forests are located in North America and Europe, where forests are generally stable and healthy.[35] Thus greater effort is required to promote sustainable forestry in developing areas of South America, Africa, and Asia.

Demand Side: Changing Consumption Patterns

The UN's Food and Agriculture Organization divides the total demand for wood products into two categories: wood that is used for fuel and "industrial roundwood," which includes logs, veneers, and wood pulp. As we see in Figure 19.7, the global demand for wood products increased steadily from 1965 to 1990—up 34 percent during this period—mainly driven by an increase in roundwood production. Since 1990 the global demand for wood products has grown only slowly, with global demand in 2015 only 5 percent greater than it was in 1990.

Figure 19.7 World Wood Production, 1965–2015



Source: FAOSTAT online database, http://faostat3.fao.org/download/F/FO/E.

Despite this recent slowdown, the FAO projects that global wood demand will grow significantly in the future. Industrial roundwood production is projected to increase by nearly 50 percent between 2005 and 2030, with the greatest increase in demand occurring in Asia and Europe. While the use of wood as a direct fuel source in developing countries is expected to decline, the FAO projects this will be more than offset by an increase in the demand for wood used for biofuels.[36]

Per-capita consumption of wood is relatively similar in developed and developing countries, but the composition of wood demand is quite different. In developed countries, about 80 percent of wood demand is in the form of industrial wood products. In developing countries, about 80 percent of demand is in the form of wood used for fuel.[37] As the global demand for fuelwood declines, an increasing share of the overall demand for wood will be for wood products such as plywood, furniture, construction lumber, and paper products.

While the overall global demand for non-fuel wood has not grown rapidly since 1990, several wood products have seen rapid growth. In particular, the global demand for paper and paperboard increased by nearly 70 percent between 1990 and 2015.[38] Like other forms of consumption, paper consumption is unequally distributed, with higher per-capita demand in developed countries. For example, annual paper consumption is about 340 kg per person in Belgium, 220 kg per person in the U.S., 170 kg per person in France, 70 kg per person in China, 50 kg per person in Brazil, 10 kg per person in India.[39]

Expanded recycling of paper and other wood products has significant potential to reduce pressure on forests. Worldwide, about half of wastepaper is now recycled. The countries with the highest paper recycling rates include South Korea (85 percent), Japan (72 percent), and Germany (70 percent). The Earth Policy Institute estimates that if every country recycled as much paper as South Korea, the amount of wood needed to produce paper would decline by a third.[40]

Low prices for paper and other wood products serve as both an incentive for greater consumption and a disincentive to expanded recycling. In some cases, direct and indirect subsidies for forest exploitation encourage the use of virgin rather than recycled paper. Internalizing environmental externalities into prices would encourage greater efficiency at all stages of the production cycle. Properly pricing wood products would increase prices for non-recycled paper and all one-time-use wood products relative to recycled-materials prices, thereby encouraging a higher recycling rate.

The demand for wood products is only one way that consumption patterns impact forests. Deforestation is often "embodied" in the demand for non-wood products, particularly crops and livestock. For example, a 2015 analysis found that nearly 50 percent of the European demand for soy products was met by soy plantations in Brazil, requiring more than 7 million hectares.[41] Another food product responsible for significant deforestation is palm oil—see Box 19.4 for more on this problem.

Policies to reduce embodied deforestation include consumer awareness programs, certification of products grown using sustainable forestry practices, reducing the demand for meat, and internalizing external costs. As consumers have become more aware of the environmental benefits of shade-grown coffee, its market share has rapidly increased. Shade-grown coffee comprised 8 percent of the world market in 2009, with penetration expected to exceed 20 percent by 2015.[42]

The global demand for meat, and beef in particular, is a significant driver of deforestation as a result of the expansion of pasture land for cattle ranching. While beef provides less than 5 percent of the world's protein it requires a majority of all agricultural land. Consumer policies to reduce the growing demand for beef can focus on the health and environmental benefits of a low- or no-meat diet. Also, consumers can encourage retailers to ban meat purchases from regions suffering from deforestation. For example, in 2009 several large retailers, including Wal-Mart, agreed to ban beef purchases from regions of the Amazon rainforest.[43]

Box 19.4
PALM OIL AND DEFORESTATION

Palm oil production has more than doubled over the last decade, with over 80 percent of global production occurring on large industrial plantations in Indonesia and Malaysia. Palm oil is the predominant cooking oil in developing countries, and is an ingredient in numerous food products as well as soaps, detergents, and cosmetics. It is the world's cheapest edible oil, with India and China being the world's largest consumers.

The expansion of palm oil production has been associated with significant deforestation. At least 55 percent of new palm oil production in Indonesia and Malaysia between 1990 and 2005 entailed intentional clearing of tropical forests. Government policies have subsidized the expansion of palm oil, including low-cost long-term public land leases in Indonesia to large corporations with political influence.

Palm oil plantations are significant contributors to climate change for two reasons. First, palm oil plantations are often established on lands that were previously carbon-rich swamp forests. The draining of these lands exposes the peaty soils to decay, releasing large amounts of carbon dioxide and methane. Second, the production and refining of palm oil is energy-intensive—each ton of palm oil results in the release of an estimated 0.86 tons of carbon dioxide.

The environmental impact of palm oil production can be reduced by improved government policies. In addition to the elimination of subsidies, future plantations can be limited to existing agricultural lands or lands that have already been deforested or degraded. As a result of pressure from consumers and environmental groups, the Roundtable on Sustainable Palm Oil (RSPO) was established in 2004 and has developed voluntary certification guidelines that minimize the negative impacts of palm oil production on the environment and local communities. The proportion of palm oil producers obtaining RSPO certification has increased rapidly, reaching 17 percent of the global total in 2016.

Sources: Boucher *et al.*, 2011; http://www.rspo.org/.

Summary

An important goal of forest management is to reconcile the differing principles of economics and ecology. Ecological sustainability has dimensions not reflected in the economic analyses of resource use. Whereas economic sustainability is concerned primarily with sustaining a flow of income over time, ecological sustainability depends on resilience—the "bounce-back" capacity of ecosystems affected by economic exploitation. Resilience depends on ecological complexity, an essential element of sustainable natural systems. But economic harvesting with maximum profit in mind often destroys complexity. Total forested area may not decline, but natural forest will be replaced with ecologically less diverse second-growth forest or with faster-growing plantation monocultures. In rapidly growing developing economies, many natural resource systems, traditionally harvested in a relatively sustainable manner, come under much heavier pressure as a market logic prevails and modern technology penetrates remote areas.

Deforestation and conversion of natural forest to plantation cause significant biodiversity loss. Values associated with biodiversity represent significant externalities rarely reflected in market prices. Growing demand for wood and wood products increases pressure on forests. Open access to many forests creates incentives for short-term exploitation without investment in replanting or sustainable forestry. In addition, many governments subsidize excessive forest clearance by making public lands available to timber companies at low prices.

Technologies such as sustainable forestry, paper recycling, and efficient materials use have great potential for conservation of scarce resources. Given the proper incentives, ecologically friendly technology and management can promote conservation, less wasteful resource use, recycling, and more efficient consumption. Recognizing the total economic value of forests, with proper internalization of positive and negative externalities, can help to create such incentives.

Key Terms and Concepts

assets

biodiversity (biological diversity)

biomass

certification

clear-cut

discount rate

flow

logistic curve/logistic growth

mean annual increment (MAI)

monoculture

optimal rotation period

payments for ecosystem services (PES)

resilience

secure property rights

stock

sustainable management

total economic value

Discussion Questions

1. Unlike ocean fisheries, forests can be privately owned, and in fact many millions of acres of forests are owned and managed by private corporations. In economic theory, private ownership should create incentives for efficient management. To what extent is this true of privately owned forests? Is efficient management also beneficial to the environment?
2. How can the timber values of forests be balanced with their value in supporting biodiversity? What changes in property regimes and forest management policies could be used to help achieve the dual goals of economic profitability and environmental preservation?
3. How can consumer action affect forest conservation and forest loss? What are the most effective ways of changing consumption patterns of wood and wood products in ways that promote forest sustainability?

Exercise

XYZ Forest Products owns a 2,000-acre tract of forest land, of which 1,000 acres are currently planted in hardwood trees (oak, beech, etc.) and 1,000 in softwoods (pine). An acre of either kind of forest contains a biomass (standing timber) of 200 tons per acre. But hardwoods are slower-growing: an acre of hardwoods will add 10 tons per acre per year of new growth, whereas an acre of softwoods will add 20 tons per acre per year.

The going price is \$500 per ton for hardwood and \$300 per ton for softwood. These prices are expected to remain stable for the indefinite future (in real terms). Two management practices are possible: clear-cutting, in which all trees are removed; and sustainable timbering, in which the amount of biomass removed annually is just equal to annual growth. The cost of clear-cutting is $40 per ton (for either kind of tree), while that for sustainable timbering is $70 per ton.

Analyze the profit-maximizing forest management policy that XYZ corporation will pursue if:

(a) Real interest rates are 3 percent per year.

(b) Real interest rates are 5 percent per year.

Now assume that XYZ is taken over by the Gargantua conglomerate, which has $100 million in debt at a 10 percent real interest rate. Analyze its probable forest management practice.

Comment on the role of the interest rate here, and suggest a government policy on forest management. Are there other considerations not apparent in the data given here that would affect policy decisions? What would you recommend if the forest were publicly rather than privately owned? How might your recommendations differ for forest management in developed versus developing countries?

Notes

1. The curves in Figures 19.1–19.3 were generated using a logistic function with the population (timber volume) at time t equal to $K/(1+ae^{-rt})$, where K is the carrying capacity, a is a constant, and r is the population growth rate.
2. This simplified formula for the sum of an infinite stream of constant values can be derived mathematically; we omit the proof here. Also, while it is admittedly unrealistic to assume that the income from sustainable management will be remain the same each year into the indefinite future, it simplifies the analysis.
3. For a more detailed treatment of the economics of timber harvesting and optimal rotation periods, see Hartwick and Olewiler, 1998.
4. For an overview of studies on valuation of biodiversity, see Bartkowski *et al.*, 2015.
5. For an overview of the state of the world's forests, see FAO, 2016.
6. FAO, 2015.
7. FAO, 2016.
8. Kim *et al.*, 2015, p. 3495.
9. See Common and Perrings, 1992; Holling, 1986.
10. WWF, http://wwf.panda.org/about_our_earth/deforestation/.
11. Ceballos *et al.*, 2015.
12. WWF, 2014.
13. Solar *et al.*, 2015.
14. Boucher *et al.*, 2011, p. 9.
15. http://www.un.org/esa/forests/forum/index.html.
16. http://www.un.org/esa/forests/pdf/ERes2007_40E.pdf.
17. Maguire, 2010.
18. http://www.scientificamerican.com/article/deforestation-and-global-warming/.
19. Ni *et al.*, 2016.
20. REDD+ is a more comprehensive approach than the original REDD version. REDD focused only on reducing deforestation in developing countries. REDD+ adds the role of conservation, sustainable forest management, and enhancement of forest carbon stocks. See https://en.wikipedia.org/wiki/Reducing_emissions_from_deforestation_and_forest_degradation.

21. http://www.un-redd.org/partner-countries.
22. Aziz *et al*., 2015.
23. http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf.
24. http://www.worldbank.org/en/news/feature/2015/12/18/outcomes-from-cop21-forests-as-a-key-climate-and-development-solution.
25. http://www.wri.org/blog/2016/01/forests-are-paris-agreement-now-what.
26. FSIV, 2009; Meyfroidt and Lambin, 2009.
27. For a review of implementation of PES for forest services, see Vedel *et al*., 2015. For an assessment of the potential impact of PES on forest management, see Matthies *et al*., 2016.
28. http://www.unep.org/forests/Portals/142/docs/our_vision/PES_Schemes.pdf; http://www.watershedconnect.com/documents/files/program_of_payments_for_ecological_services_in_costa_rica.pdf.
29. http://www.unesco.org/new/en/media-services/single-view/news/unesco_announces_selection_of_13_new_biosphere_reserves#.V9Bw0TWuyvU.
30. Shade-grown coffee leaves forest trees standing, with coffee bushes beneath, while sun-grown coffee requires complete removal of forest cover.
31. See Myers, 1996; Wertz-Kanounnikoff, 2008.
32. Natural Resource Economics, 2016.
33. Daly-Hassen, 2013.
34. Bernetti *et al*., 2013.
35. FSC, 2016.
36. FAO, 2009.
37. FAO, 2002.
38. FAOSTAT online database.
39. Anonymous. "I'm a Lumberjack," *The Economist*, April 3, 2012, http://www.economist.com/blogs/graphicdetail/2012/04/daily-chart-0.
40. Earth Policy Institute. "Reduce, Recycle, and Replant—Restoring the World's Forests, Data Highlights," April 28, 2010, http://www.earth-policy.org/data_highlights/2010/highlights10.
41. WWF, 2015.
42. ITC, 2011.
43. Boucher *et al*., 2012.

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Web Sites

1. **www.cifor.org.** Web site of the Center for International Forestry Research, a nonprofit, global facility that conducts research to enable more informed and equitable decision making about the use and management of forests in less developed countries, including analysis of the underlying drivers of deforestation and degradation.

2. **www.wri.org/our-work/topics/forests.** The World Resources Institute page on forest loss and policies for sustaining forests.

3. **www.ran.org/forests/.** Information about rainforests from the Rainforest Action Network, an environmental group that campaigns to protect rainforests around the world.

CHAPTER 20

Water: Economics and Policy

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Chapter 20 Focus Questions

- What is the extent of global water scarcity?
- Can water shortages be addressed by expanding supplies?
- Can water markets promote more efficient water use?
- Is water a private good or a common-property resource?

20.1 GLOBAL SUPPLY AND DEMAND FOR WATER

Water is a unique natural resource that forms the basis for life on earth. Ninety-seven percent of the Earth's water is salt water and only 3 percent is freshwater, of which 70 percent is in solid form, captured by the polar ice caps and by glaciers (Figure 20.1). Of the 30 percent of freshwater that is available in its liquid form, most is in underground aquifers. The freshwater that makes up all of the terrestrial sources such as rivers and lakes only represents 1 percent of the planet's freshwater.

Water can be characterized as a renewable resource, since it can generally be reused indefinitely as long as it is not severely polluted. Also, water is continually purified in a process known as the **hydrologic cycle** (see Figure 20.2). (Hydrology is the scientific study of the distribution and movement of water on the earth's surface, underground, and in the atmosphere.) Water evaporates into the atmosphere from lakes, rivers, oceans, and through the evapotranspiration of plants and other living organisms, then returns to the earth's surface as precipitation that replenishes freshwater sources.

Many of the principles of renewable resource management apply to water systems, but although surface water can be considered a renewable resource, it is still available in limited supply. The **flows** of freshwater that are recycled in the hydrologic cycles can become **stocks** in two types of natural reservoirs: bodies of surface water such as lakes and rivers, and stocks of groundwater, which are found in aquifers.

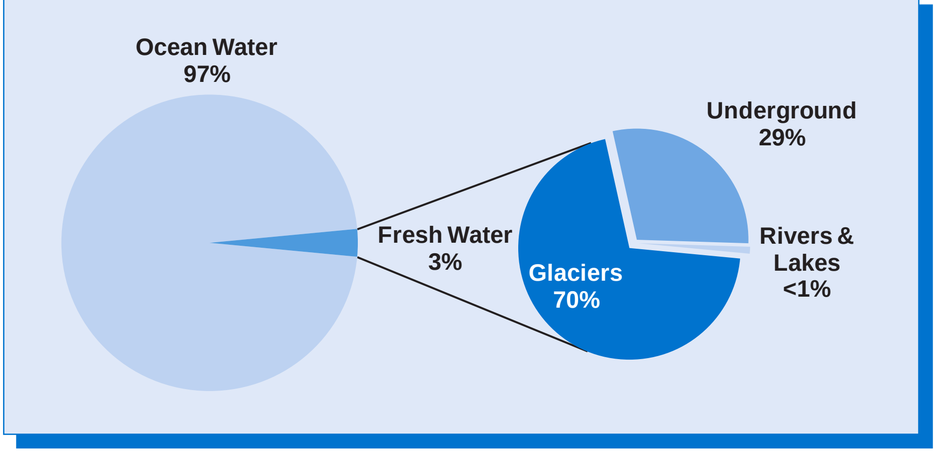
While aquifers are replenished as a result of surface water infiltration, most aquifers have very long replenishment times, making them essentially nonrenewable resources on a human time scale. Aquifers under the Sahara, for example, are thousands of years old

hydrologic cycle the natural purification of water through evaporation and precipitation.

stock the quantity of a variable at a given point in time, such as the amount of water in a lake, or the amount of timber in a forest, at a given time.

flow the quantity of a variable measured over a period of time, including physical flows, such as the flow of a river past a given point measured in cubic feet per second, or financial flows, such as income over a period of time.

Figure 20.1 The Composition of the Planet's Water



Source: World Business Council for Sustainable Development, 2005. *Facts and Trends: Water*, http://www.unwater.org/downloads/Water_facts_and_trends.pdf.

and are sometimes referred to as "fossil water." Thus the analysis of water systems combines elements of renewable and nonrenewable resource theory.

> [E]vaporation fueled by the sun's energy lifts 500,000 cubic kilometers of moisture into the atmosphere each year—86 percent from the oceans and 14 percent from the land. An equal amount falls back to earth as rain, sleet, or snow, but it is distributed in different proportions: whereas the continents lose about 70,000 cubic kilometers through evaporation, they gain 110,000 through precipitation. As a result, roughly 40,000 cubic kilometers are transferred from the sea to the land each year.[1]

The total available supply of 40,000 cubic kilometers is equivalent to about 5,500 cubic meters per person per year. Hydrologists have established that, considering the water needs of modern societies, a threshold of 2,000 cubic meters per person per year represents the level above which a population can be sustained comfortably. But while the total global water supply is sufficient to meet human needs, not all water can be captured for human use. As much as two-thirds of the total water supply runs off as floods. Some water must also be allocated to meet ecological demands, such as supplying wetlands and wildlife habitat.

Most important, water is not evenly distributed geographically and seasonally. Some regions of the world have abundant water resources, while others suffer from a scarcity of water. A country that has an available water supply between 1,000 and 1,700 cubic meters per person per year is classified as **water stressed**.[2] If water supplies are below 1,000 cubic meters per person per year, the country is classified as **water scarce**, causing a severe constraint on food production, economic development, and protection of natural systems. A country faces a situation of **absolute water scarcity** when freshwater supplies drop below 500 cubic meters per person per year.

water stressed term used for countries where freshwater supplies are between 1,700 and 1,000 cubic meters per person per year.

water scarce term used for countries where freshwater supplies are less than 1,000 cubic meters per person per year.

absolute water scarcity term used for countries where freshwater supplies are less than 500 cubic meters per person per year.

Figure 20.2 The Hydrologic Cycle

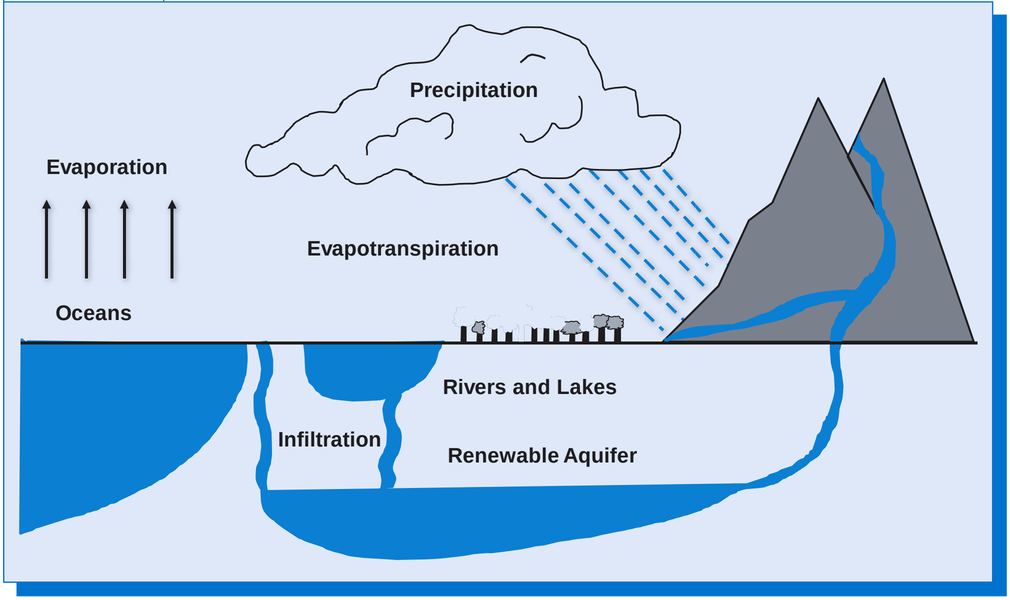
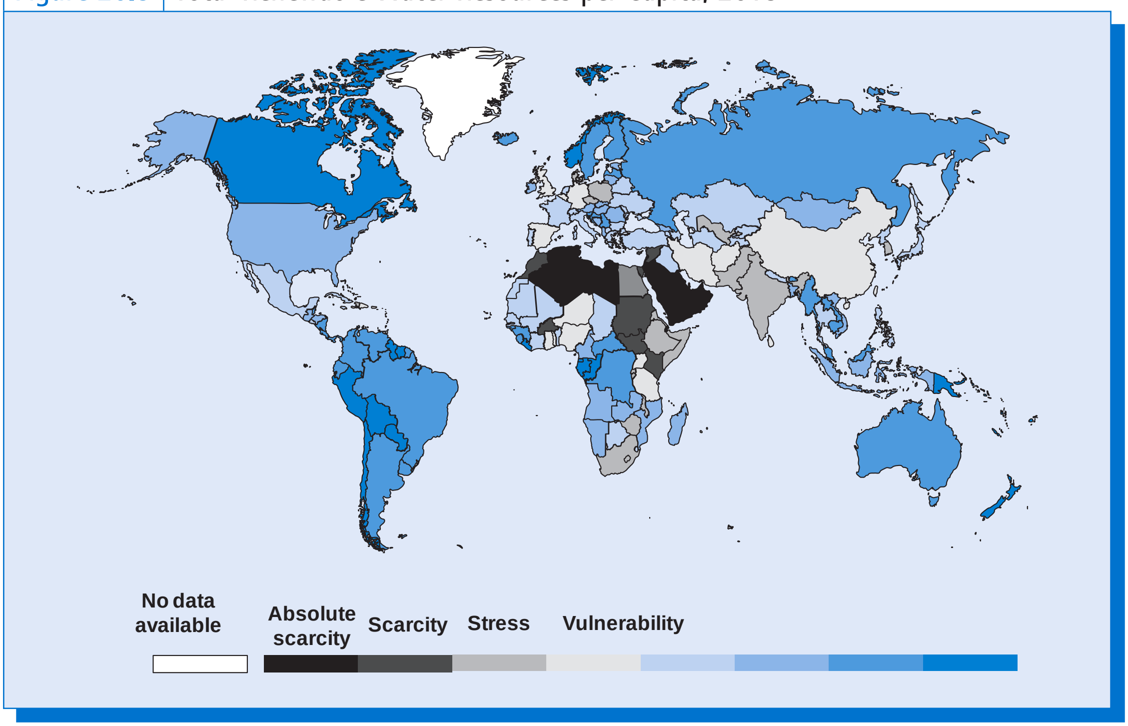


Figure 20.3 displays national averages of freshwater supplies available per person per year. Table 20.1 shows freshwater availability in major regions of the world. The Middle East and North African region already experiences a situation of absolute water scarcity (average 500 cubic meters per person per year) with a current population of 479 million (in 2015) expected to increase to 779 million in 2050.[3] Sub-Saharan Africa suffers from water scarcity (1,000 cubic meters per person per year) with a population of 949 million (in 2015) expected to double by 2050.[4] According to a 2008 UNEP report:

> [According to projections], more than 2.8 billion people in 48 countries will face water stress or scarcity conditions by 2025. Of these countries, 40 are in West Asia, North Africa or sub-Saharan Africa. Over the next two decades, population increases and growing demands are projected to push all the West Asian countries into water scarcity conditions. By 2050, the number of countries facing water stress or scarcity could rise to 54, with a combined population of four billion people—about 40 percent of the projected global population of 9.4 billion.[5]

Water shortages will be exacerbated in some regions because of climate change. The Intergovernmental Panel on Climate Change (IPCC), comparing several projection scenarios, has stated that "broadly, water resources are projected to decrease in many mid-latitude and dry subtropical regions, and to increase at high latitudes and in many humid mid-latitude regions."[6] Assuming an increase in global average temperature of 2°C above the 1980–2010 mean, and combining five climate models with 11 hydrological models (55 scenarios), the IPCC shows that there is a strong likelihood of a decrease of 30–50 percent in runoff for the

Figure 20.3 **Total Renewable Water Resources per Capita, 2013**



Source: WWAP, with data from the FAO AQUASTAT database, reproduced in United Nations World Water Development Report, 2015.

Note: Blue shading denotes water availability per person (the darker the blue, the more water-abundant).

Table 20.1 Water Availability per Region, 2012

Region	Average Water Availability (cubic meters/person)
Middle East and North Africa	500
Sub-Saharan Africa	1,000
Caribbean	2,466
Asia/Pacific	2,970
Europe	4,741
Latin America	7,200
North America (including Mexico)	13,401

Sources: FAO, Aquastat, 2013; UNESCO, 2012, http://vitalsigns.worldwatch.org.

following regions of the world: Southern Europe, Eastern Europe and the Ukraine, North Africa (Morocco, Algeria, Tunisia), Middle East (Turkey, Syria, Lebanon, Israel, Palestine, Jordan, Iraq, Iran, Afghanistan), South Africa, Southern Latin America (Chile, Southern Brazil, Uruguay, Paraguay, Argentina), Southwest Australia. At the opposite side of the spectrum, wet regions like India and Bangladesh are likely to experience an increase of 30–50 percent in runoff.

As warmer temperatures speed up the hydrological cycle, wet areas will tend to become wetter, increasing the likelihood of flooding (particularly in the Indian subcontinent).

Box 20.1

THE WESTERN UNITED STATES: ONE HUNDRED YEAR DROUGHT?

Drought conditions have been widespread in the Western United States since the beginning of the twenty-first century. Nine states have experienced severe droughts in recent years: California, Arizona, Colorado, Kansas, Nevada, Oklahoma, Oregon, Texas, and Utah. According to NASA scientists, in December 2014, California's reserve of water was barely enough for one year of water use. Fortunately, the very wet winter of 2015–2016 partially replenished reservoirs, which had been at their historical lowest point in 2015. But NASA projections for the future predict that there is a strong likelihood that "droughts in the U.S. Southwest and Central Plains during the last half of this century could be drier and longer than drought conditions seen in those regions in the last 1,000 years."

Assuming no significant policy changes, projections by the Intergovernmental Panel on Climate Change indicate that *average* rainfall in the American West will be less than the average during the 2000–2004 drought. Climate change models "suggest that a coming megadrought—a prolonged, multidecade period of significantly below-average precipitation—is possible and likely in the American West."

Emergency measures instituted during recent droughts, such as lawn-watering and other restrictions, may need to be made permanent. The extent of irrigated agriculture may need to be reduced. While there may still be time to avoid the risk of megadroughts, "there can be little doubt that what was once thought to be a future threat is suddenly, catastrophically upon us."

Sources: Schwalm *et al.*, 2012; NASA, "11 Trillion Gallons to Replenish California Drought Loss," https://www.nasa.gov/press/2014/december/nasa-analysis-11-trillion-gallons-to-replenish-california-drought-losses; Thomas Frohlich and Mark Lieberman, "Nine States Running Out of Water," http://247wallst.com/special-report/2015/04/22/9-states-running-out-of-water/.

Currently arid and semiarid areas are likely to become drier, increasing the probability of droughts.[7] (For more on the impact of climate change on precipitation patterns in the western United States, see Box 20.1.)

Water Demand, Virtual Water, and Water Footprint

To consider these challenges in more depth, we turn to a detailed analysis of the uses of water in modern societies. Water demand can be measured in a number of ways; the simplest is the amount of total freshwater withdrawal for various sectors of the economy.

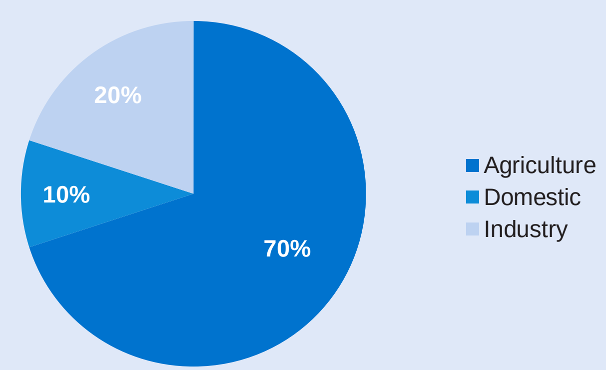
The largest water consuming sector is agriculture. Although 80 percent of the world's cropland is rain fed, the 20 percent that requires irrigation produces 40 percent of the world's food supply.[8] The water needed for irrigated agriculture amounts to 70 percent of global water withdrawals.[9] Another 20 percent of global water withdrawals is for industrial demands, including electricity generation. Only 10 percent of water is used to meet municipal and domestic demands (see Figure 20.4).

These percentages are global averages, but they vary significantly from country to country. In the United States, for instance, irrigation amounts to 41 percent of the nation's total freshwater withdrawals, while industry accounts for up to 46 percent of water withdrawals, especially for thermoelectric power generation, which needs large amounts of water cooling for steam-driven turbine generators.[10] In the developing world, freshwater withdrawals are often mostly used for agriculture (for example, agriculture accounts for 86 percent of water withdrawals in Egypt, 94 percent in Ethiopia, and 95 percent in Vietnam).

In order to analyze the full impact of human activity on water resources, scientists have proposed the concept of **virtual water**,[11] which takes into account water that is used throughout the production process for a particular good or service. Agricultural goods need water to grow plants and to raise cattle and other livestock. Industrial goods require water as raw material or as part of the production process. Both agricultural and industrial sectors also consume water indirectly through their demand for energy, which is particularly water-intensive.

virtual water water embedded in goods or services, based on water used as an input throughout the production process.

Figure 20.4 Global Water Withdrawals for Agricultural, Industrial, and Municipal Use



Source: FAO, Aquastat (updated September 2014), http://www.fao.org/nr/water/aquastat/tables/WorldData-Withdrawal_eng.pdf.

The energy sector uses water at all stages of energy extraction, production and consumption. Conventional natural gas is the least water intensive fuel, using only one-fifth as much water as conventional oil, whereas the use of unconventional oil tar sands requires 20 times more water than conventional oil. Natural gas produced by hydraulic fracturing, or "fracking," also requires much larger amounts of water than conventional natural gas production. Biofuels produced from irrigated fields of corn or soy require 3,000 times more water than conventional oil.

As an example of virtual water use through energy use, a roundtrip by car between New York City and Washington D.C. requires an amount of energy equal to 2 million BTUs (British Thermal Units), which would translate into 5 gallons of virtual water if the trip was done with a vehicle running on natural gas, 32 gallons of water if it was running on conventional oil, but 616 gallons of water if the car was running on oil coming from tar sands. If the vehicle was running on biofuels, this roundtrip would require 35,616 gallons of water using corn-based biofuel, and 100,591 gallons of water using soy-based biofuel.[12]

Table 20.2 presents the amount of virtual water embedded in some common goods.

Measures of virtual water can be used to develop the concept of a **water footprint**. The water footprint of an individual, household, corporation, city, or country is an indicator of total impact on freshwater resources, including both direct and indirect uses of water. The water footprint of the average person on the planet is 1,056 gallons of water per day—that's enough to fill up 21 standard bathtubs.[13] The average water footprint of an American citizen is more than twice the global average, amounting to 2,220 gallons of water per day, which is equivalent to 44 full bathtubs of water. In the USA, the average water footprint per year per capita is as much as the water needed to fill an Olympic swimming pool (2,842 cubic meters).[14]

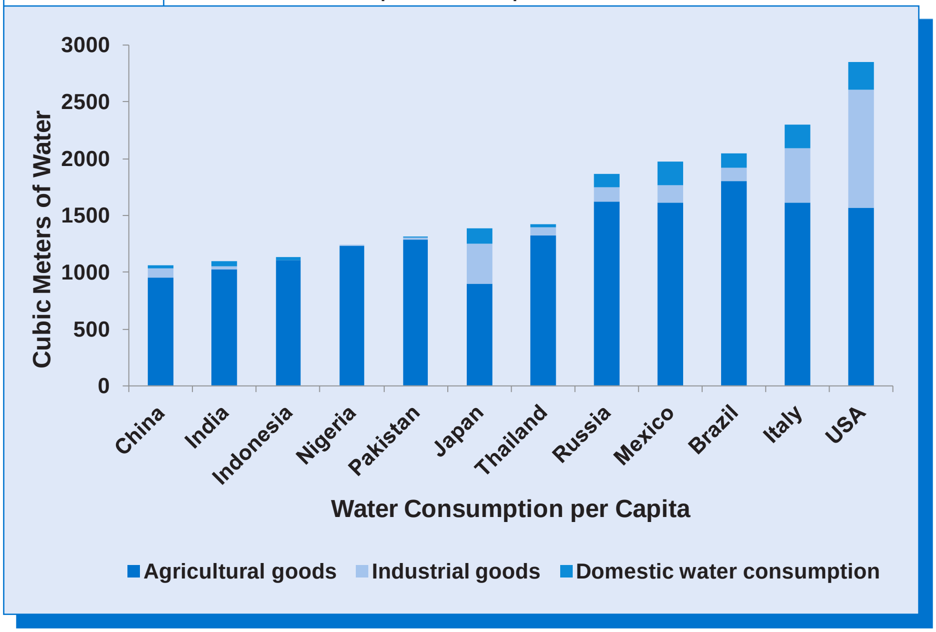
water footprint the total amount of water consumed by a human entity—individual, family, city, corporation, or country—whether directly or indirectly, calculated by summing all the virtual water embedded in the products, energy, and services used by this entity.

Table 20.2 Virtual Water Embedded in a Selection of Products, per Unit of Product (in liters: 1 gallon = 3.78 liters)

Product	Virtual-Water Content (liters)
1 sheet of paper (80 g/m2)	10
1 tomato (70 g)	13
1 slice of bread (30 g)	40
1 orange (100 g)	50
1 apple (100 g)	70
1 glass of beer (250 ml)	75
1 glass of wine (125 ml)	120
1 egg (40 g)	135
1 glass of orange juice (200 ml)	170
1 bag of potato crisps (200 g)	185
1 glass of milk (200 ml)	200
1 hamburger (150 g)	2,400
1 pair of shoes (bovine leather)	8,000

Source: Hoekstra and Chapagain, 2008, p. 15.

Figure 20.5 National Water Footprint for Selected Countries, 1997–2001 (in Cubic Meters per Person per Year)



Sources: Hoekstra and Hung, 2007, pp. 44; also available at http://waterfootprint.org/en/resources/interactive-tools/national-water-footprint-explorer/.

Figure 20.5 presents water footprints for a selection of countries, calculated in cubic meters per person per year. As seen in the figure, the water footprint of people in lower-income countries is significantly less than the U.S. footprint, primarily because domestic and industrial uses are much less.

Virtual Water Trade

Water footprints take into account all the water embedded in the goods and services consumed in a country, regardless of whether this water comes from the national resources inside the borders of the country or whether it comes from other parts of the world. An invisible circulation of water takes place between countries through trade: water-scarce countries can consume imported products that would have been too water-consuming to produce with their own water resources.

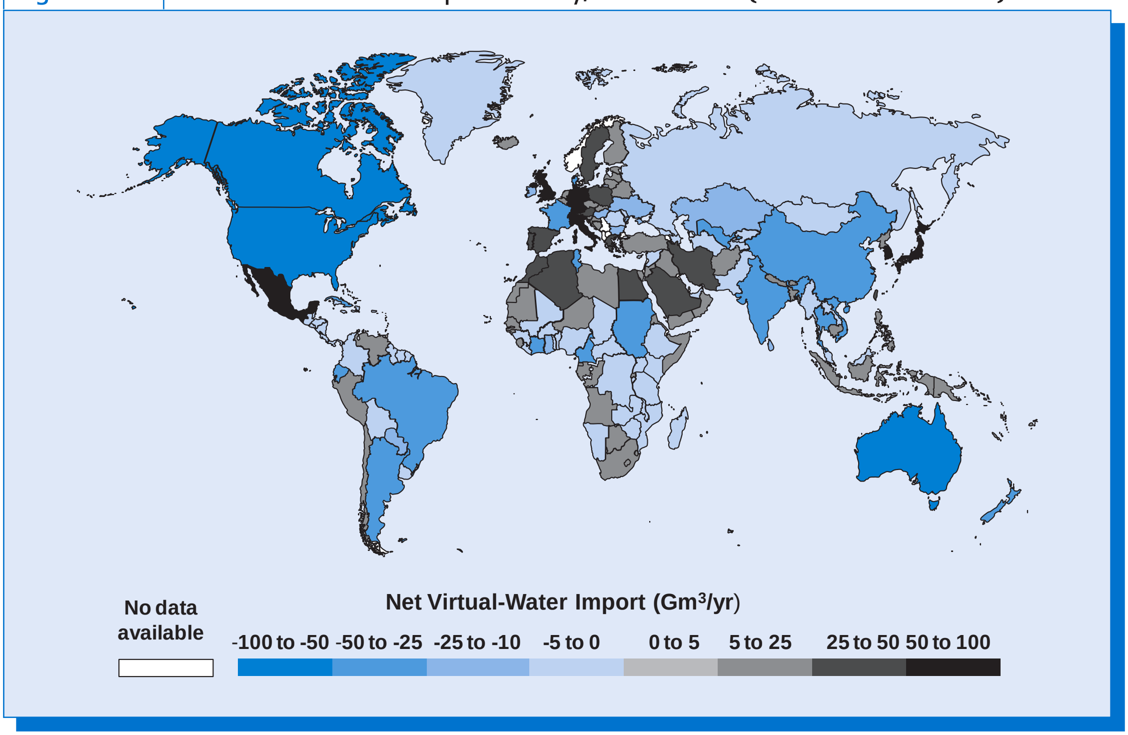
But trade does not necessarily follow a logical pattern in terms of water transfer. The cotton industry, for instance, is particularly water-intensive, and a single cotton T-shirt contains 2,700 liters of virtual water. Cotton is often produced in water-stressed or water-scarce countries, such as India, Pakistan, or Egypt. The water footprint of the exports of cotton from India to Europe represents more than 5 billion cubic meters of water per year,[15] while two-thirds of the population of India (769 million) lacks access to improved sanitation and 77 million lacks access to safe water.[16] European countries, on the other hand, which are far from being water-scarce, have living styles that require massive imports of water-intensive goods. As a result, 40 percent of Europe's water footprint lies outside of its borders; 69 percent in the case of Germany.[17]

Figure 20.6 shows a map of the world identifying countries which are net "importers" of virtual water (varying shades of grey) and net "exporters" of virtual water (varying shades of blue). If we compare this figure with Figure 20.3, we observe that most of the countries that are water abundant tend to be net exporters of virtual water, while countries that are water-scarce tend to be net importers of virtual water. However, there are important exceptions to the rule, as many of the Asian countries that are experiencing water stress are virtual water exporters, including India, Pakistan, and China. On the other hand, countries that are relatively water-abundant, such as Italy or Japan, are nevertheless virtual water importers.

Hydrologists express concern that once water is removed from a watershed (through the export of virtual water), it is irreversibly removed from the local hydrological cycle as well, which in turn reduces evaporation, heating up the atmosphere.[18] Countries which are net virtual water exporters are therefore unknowingly trapping themselves in a vicious circle where the more virtual water they export, the drier their climate becomes, which is of particular concern for developing countries that are already water stressed or water scarce.

Perverse effects of virtual water transfers are observed within developed countries as well. In the U.S., virtual water trade is emptying the Colorado and Rio Grande Rivers and depleting the Ogallala Aquifer.[19] In Australia, which is a net exporter of 64 billion cubic meters of virtual water each year, shipping out more water than it takes in, "a country continually struggling with unreliable rainfall and severe drought allows more virtual water to be lost than any other nation on the planet."[20] And in water-abundant Canada, the province of Alberta is expected to become the first water "have-not" province under the pressure of intensive livestock operations in anticipation of large export demand for meat.

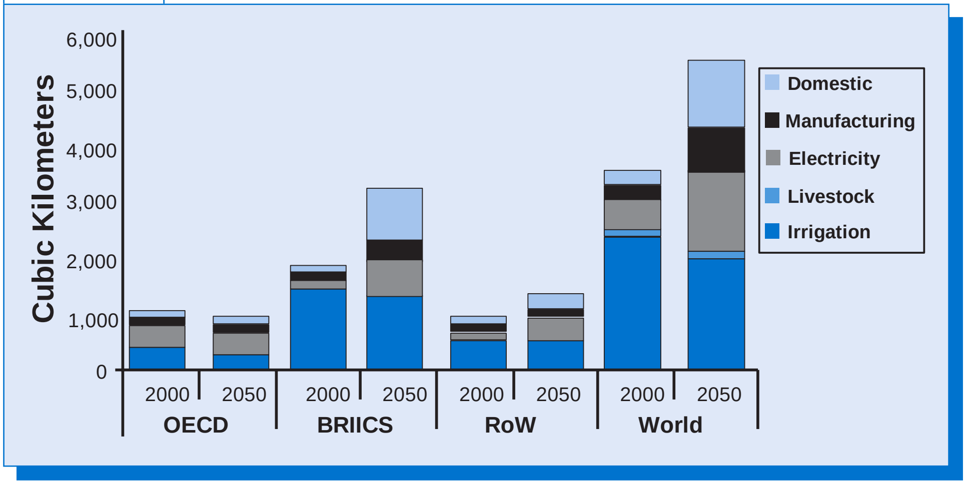
Figure 20.6 **Virtual Water Balance per Country, 1997–2001 (Billion Cubic Meters)**



Source: Hoekstra and Chapagain, 2008, pp. 84–85.

Note: Countries shown in blue (negative net virtual water import) are net virtual water exporters.

Figure 20.7 Global Water Demand, 2000 and 2050



Source: OECD, 2012.

Note: BRIICS = Brazil, Russia, India, Indonesia, China, South Africa; OECD = Organization for Economic Cooperation and Development; RoW = rest of world.

The Future of Water: Horizon 2050

Global water demand is projected to increase by 55 percent between 2000 and 2050, as shown in Figure 20.7. All the demand growth is expected to occur in developing countries, mainly China and India. While the global demand for irrigation water is actually projected to decline in the coming decades due to increased irrigation efficiency, significant growth is expected for manufacturing, domestic, and electricity needs. According to the OECD, "In the absence of major policy changes and much better water management the situation will deteriorate and water availability will become increasingly uncertain."[21]

One piece of good news is that access to safe drinking water supplies is expanding in developing countries. One of the Millennium Development Goals set by the United Nations was to halve the proportion of the world's population without access to safe drinking water between 1990 and 2015. This goal was met ahead of schedule, in 2010, when an estimated 89 percent of the world's population had access to safe drinking water.[22] However, progress in expanding access to safe water has been uneven. About half the progress occurred in China and India, while in some African countries safe water access has declined since 1990. Further improvement in water security is therefore one of the Sustainable Development Goals adopted by the United Nations in 2015.[23]

20.2 ADDRESSING WATER SHORTAGES

Water shortages can be addressed using two basic approaches: from the supply side or the demand side. Given the extent of projected water shortages in some regions, a "magic bullet" solution is unlikely. A range of options will be needed.

> We have a menu of options, but the status quo is not one of them. In the United States, the usual response to water shortages is to divert more water from rivers, build more dams, and drill more groundwater wells. These traditional alternatives are not viable

Box 20.2
WATER AND CONFLICT

Many conflicts have erupted throughout history between populations clashing over access to scarce water sources. The first archeological signs of water conflicts date as far back as 2500 B.C. in Mesopotamia. In the conflicts of our times, water is one of the leading factors in some of the regional contexts where water scarcity is most pronounced. The civil war that has devastated Syria since 2011 was strongly related to water shortage issues. A climatic event, the prolonged six-year drought from 2006 to 2011, caused the ruin of hundreds of thousands of small-scale farmers and forced them to migrate with their families to the outskirts of several major cities, such as Aleppo, Damascus, Hama, Homs, and Dara'a. This impoverished and destitute population formed the demographic basis for a popular revolution against the Assad regime in 2011, ushering in a period of extreme instability and civil war.

In one of the most protracted conflicts of our times, between the State of Israel and the Palestinian people, access to the water aquifers underneath the hills of the West Bank is an important factor. A World Bank report indicates that Israelis use four-fifths of the West Bank groundwater resources, and the Palestinians only one-fifth. Israelis use 240 cubic meters of water per person per year, compared with 75 cubic meters per person per year for West Bank Palestinians. In some areas of the West Bank, Palestinians are surviving on as little as 10 to 15 liters a person each day, which is at or below humanitarian disaster response levels recommended to avoid epidemics. The amount recommended by the World Health Organization is at least 100 liters per day.

For Palestinians in the Gaza Strip, water supply depends on the coastal aquifer (also shared with Israel) that has become increasingly saline and polluted. Because of the conflict, there has been little or no investment in water infrastructure in decades and only 5–10 percent of the available water is clean enough to drink. The issue of water resources has been an essential dimension of all the rounds of diplomatic talks between Israelis and Palestinians since the 1990s.

Sources: Gleick *et al.*, 2014, *The World's Water*, Volume 8: p. 147ff: "The Syrian Conflict and the Role of Water" and p. 174ff: "Water Conflict Chronology"; World Bank Middle East and North Africa Region Sustainable Development, *West Bank and Gaza*: *Assessment of Restrictions on Palestinian Water Sector Development*, April 2009; Israeli Human Rights Organization B'Tselem, http://www.btselem.org/topic/water.

solutions. Other ideas—surreal ones—include towing icebergs from the Arctic, importing water from British Columbia, and seeding clouds. These ideas reflect a misguided hope that there is a new oasis out there, somewhere, that will obviate the need to examine carefully how and for what we use water. More sensible approaches include conservation, desalination, and reuse of treated municipal effluent. Yet even communities that have embraced these measures still face ominous water futures.[24]

Increasing Water Supply: Aquifers, Dams, and Desalination

Past water management policies have generally focused on ways to increase the supply of water. In regions where freshwater supplies are insufficient to meet demand, additional water has often been obtained by extracting groundwater from aquifers. While underground aquifers are normally recharged by water seepage, in most cases withdrawal rates greatly exceed the rates of recharge.

Countries such as Saudi Arabia and Libya rely on "fossil" groundwater from ancient aquifers in desert areas, which now have practically no recharge and are likely to be depleted in the next 40 to 60 years. In the western United States, the Ogallala Aquifer is also severely depleted, and as a result irrigated area has started to shrink. Similar problems affect aquifers in North China and in India. (For more on the exploitation of aquifers around the world, see Box 20.3.)

Another way to increase water supplies is to construct dams. Dams can capture seasonal floodwater that would otherwise be unavailable for human use, as well as providing hydroelectric power and irrigation. Worldwide about 48,000 large dams are in operation, about half of them in China.[25] These dams provide 19 percent of the world's electricity. More dams are still being built, mainly in China, Iran, Japan, and Turkey, but the best sites are already in use. Existing dams are often affected by problems of siltation, and new large dam proposals have been criticized for the environmental and social damage that results from the flooding of large areas.[26] For example, the Three Gorges Dam in China, the largest hydroelectric dam in the world, displaced 1.3 million people and disrupted the habitat of dozens of endangered species.

The World Wildlife Fund reports that large dams (more than 15 meters high) built to provide hydroelectricity and flood irrigation are killing the ecosystems of the major rivers in the world. Only 21 (12 percent) of the world's longest rivers run freely from source to sea. The world's large dams have wiped out species, flooded huge areas of wetland, forest, and farmland, and displaced many millions of people. Dams reduce biodiversity, decrease fish populations, lower crop production, disrupt the flow of nutrients needed for water health, and contribute to global warming by trapping methane and rotting vegetation in their reservoirs. Canadian scientists have made a preliminary estimate that reservoirs worldwide release up to 70 million tons of methane and around a billion tons of carbon dioxide every year. Big dams also affect the water supply. Toxic algae blooms have rendered some reservoirs unfit to drink. And because they greatly increase the surface area of water, dams increase evaporation. About 170 cubic kilometers of water evaporate from the world's reservoirs every year, more than 7 percent of the amount of fresh water consumed by all human activities.[27]

Box 20.3
DEMAND FOR WATER OUTSTRIPS SUPPLY

According to an analysis of global groundwater supplies published in 2012, nearly one-quarter of the world's population lives in areas where groundwater is being withdrawn faster than it can be replenished. This includes many of the world's major agricultural regions, including the Central Valley in California, the Nile delta in Egypt, and the Upper Ganges in India. In addition to providing water for irrigation, water stored in underground aquifers for thousands of years supplies basic human needs, manufacturing demands, and water for wildlife habitat.

"This overuse can lead to decreased groundwater availability for both drinking water and growing food," says Tom Gleeson, a hydrogeologist at McGill University in Montreal, Quebec, and lead author of the study. Eventually, he adds, it "can lead to dried up streams and ecological impacts."

The study found that some aquifers are being depleted at an alarming rate. For example, the geographical area dependent upon the Upper Ganges aquifer is more than 50 times the size of the aquifer itself. Gleeson notes that "the rate of extraction is quite unsustainable there."

However, Gleeson points out that remaining groundwater supplies, overall, are quite large. As much as 97 percent of the fresh, unfrozen water on the planet is groundwater. "It's this huge reservoir that we have the potential to manage sustainably," he says. "If we choose to."

Source: Mascarelli, 2012.

Because of the vast amounts of seawater on the planet, **desalination** has appeal as a potential source of virtually unlimited supply. However, cost is a significant barrier to desalination. Removing salt from seawater requires large amounts of energy. While desalination costs have declined as technology has improved, it currently costs about $0.50 to $1.00 per cubic meter to desalinate seawater,[28] which is usually more expensive than obtaining water supplies from surface water or groundwater. For example, in an analysis of water supply options in San Diego, California, desalination costs were estimated to be $1,800–$2,800 per acre-foot (AF) while the supply costs were $400–$800 per AF for surface water and $375–$1,100 per AF for groundwater.[29] While desalination may make economic sense in some very dry regions, it is unlikely to supply a significant amount of the planet's water in the future:

desalination the removal of salt from ocean water to make it usable for irrigation, industrial, or municipal water supplies.

> Despite major advancements in desalination technologies, seawater desalination is still more energy intensive compared to conventional technologies for the treatment of fresh water. There are also concerns about the potential environmental impacts of large-scale seawater desalination plants, which must dispose of large volumes of highly saline brine that is the byproduct of desalination.[30]

Water Demand Management

One of the ways that we can alter the projected trend of increasing water demand in Figure 20.7 is to increase water use efficiency. The greatest efficiency gains can be made in agriculture. Whereas traditional irrigation by flooding or channeling water by gravity is inefficient (60 percent of the water is lost by evaporation or infiltration), new techniques of **micro-irrigation** by drip systems allow an efficiency of 95 percent.[31] Also, technologies that permit better monitoring of soil and weather conditions can more accurately determine appropriate irrigation needs.

micro-irrigation irrigation systems that increase the efficiency of water use by applying water in small quantities close to the plants.

For nonagricultural uses, recycling and reuse of wastewater can reduce water demand. For example, through a graywater system, water used for such purposes as laundry and bathing can also be used to irrigate landscaping. Water use standards for devices such as dishwashers, toilets, and showerheads can reduce domestic water needs. Leak detection and repair, especially in municipal water supply lines, can also help reduce water consumption.

Economic research shows that conservation is generally the cheapest way to address water shortages. In the San Diego study mentioned above, the cost of conservation was estimated at between $150 and $1,000 per AF, based on a range of conservation options. The study concludes:

> Conservation appears as the most attractive of the seven water solutions analyzed for San Diego County by a wide margin. These findings suggest that solving San Diego County's water challenge may rest significantly on the demand side.[32]

Water conservation can be realized using several approaches, including price-based and nonprice approaches. Nonprice approaches can be classified into four basic categories:[33]

1. *Required or voluntary adoption of water-conserving technologies*: This includes setting standards for appliance efficiency or offering water customers rebates or even free items such as low-flow showerheads.

2. *Mandatory water use restrictions*: These are often implemented in response to drought conditions and may include restrictions on watering lawns, washing cars, or filling swimming pools.
3. *Education and information*: These include mailing information to customers about ways to reduce water use, offering talks on water conservation, or airing public service messages on TV or the Internet.
4. *Innovative institutional design of common-property resources*: In some locations traditional patterns of communal water use can be promoted or recreated as an alternative to large-scale water supply (see Section 20.5).

While these nonprice methods are all useful to curb demand, economists tend to focus on **water pricing** as the most effective way to induce water conservation. Prices should serve as indicators of economic scarcity, reflecting physical limits and environmental externalities. For various social and political reasons, however, governments have maintained low water prices, particularly for agriculture. We now turn to a discussion of water pricing, in theory and in practice.

> **water pricing** setting the price of water to influence the quantity consumed.

20.3 WATER PRICING

Our study of water pricing requires us to recall several of the concepts discussed earlier in the text. First we need to differentiate between value and price.[34] The value of water to consumers is reflected in willingness to pay for it, as discussed in Chapters 3 and 6. The difference between willingness to pay for water and its price is its net benefit, or consumer surplus. In theory, consumers will continue to purchase water as long as their willingness to pay for it exceeds the price. But this market analysis does not tell the whole story. While water has obvious use values, including for domestic uses and irrigation, it also has nonmarket and nonuse values, such as for recreation and wildlife habitat.[35]

We must also differentiate between the average cost of supplying water and its marginal cost. The marginal cost is the cost of supplying one additional unit of water. The average cost is simply the total supply cost divided by the number of units supplied. The distinction is important because water utilities are normally **regulated monopolies**. A company seeking to maximize profits will produce as long as marginal revenue exceeds marginal supply costs (i.e., as long as it is making a profit on each unit). While an unregulated monopolist can set its price to maximize profits, a regulated monopolist, such as a water utility, is normally restricted in its ability to set prices.

> **regulated monopolies** monopolies that are regulated by an external entity, for example through controls on price or profits.

Water utilities in the United States are either privately or publicly owned. Private water utilities are permitted to make a reasonable profit, while municipal utilities' prices are set to cover their total supply costs, considering both fixed and variable costs. In either case, regulatory bodies normally set water prices using **average-cost pricing**, without any consideration of marginal costs. For a municipal utility, setting price equal to average cost means that they will just break even.[36] A private utility would be allowed to charge a price somewhat above average cost in order to make a profit.

> **average-cost pricing** a water pricing strategy in which price is set equal to the average cost of production (or equal to average cost plus a profit mark-up if the water utility is a for-profit entity).

But does average cost pricing result in an efficient level of water supply? We know that the socially efficient level of provision for a good occurs where marginal benefits equal marginal costs. Thus average-cost pricing is unlikely to result in an efficient level of water supply. Normally the marginal cost of water supply is quite low relative to its average cost because supplying water requires significant up-front capital costs, such as for pipes and treatment facilities. This might seem to imply that the efficient price for water should be lower than its average cost. But we also need to consider the externality costs of supplying water, which may include such impacts as the loss of wetlands and wildlife habitat. For a socially efficient price, any externality costs should be considered when calculating the average cost of supply, as discussed in Chapter 3. In this respect, failing to account for water's externality costs implies that average-cost pricing may result in a price that is too low. So it is unclear whether average-cost pricing results in a price that is too high or too low from the perspective of economic efficiency.

For the management and pricing of groundwater, a nonrenewable resource, we also need to consider our analysis from Chapter 5. Recall that the efficient allocation of a nonrenewable resource over time requires us to take into account the externality costs imposed on future generations if future supplies will be insufficient to meet their demands. We concluded that these costs can be internalized by charging a user cost to the current generation. This is rarely done in practice for groundwater, again suggesting an inefficient allocation of water.

Further complicating our analysis is the fact that water is often subsidized by the government, in particular for irrigation uses.

> Many authors have called for the elimination of irrigation subsidies, at times suggesting that water is a commodity and should be priced accordingly. They describe the potential gains in irrigation efficiency and the public value of communicating scarcity conditions through market-based prices. Other authors suggest that subsidies can be justified because irrigation projects provide both public and private goods, or that higher water prices will reduce agricultural net revenues without motivating notable reductions in irrigation diversions.[37]

In regions where irrigation has significant environmental impacts, it may be more appropriate to tax water rather than subsidize it. Consider some of the environmental damage caused by irrigation:

> An excessive withdrawal of water for irrigation is clearly impacting the environment in some areas. For example, the Colorado River often contains essentially no water by the time it crosses the border into Mexico, owing to both urban and agricultural withdrawals. In fact, in most years, the Colorado River doesn't make it to the ocean. This has consequences for the river and its riparian ecosystems, as well as for the delta and estuary system at its mouth, which no longer receives the recharge of fresh water and nutrients that it normally did. The same is true for the Yellow River in China. The San Joaquin River in California is so permanently dewatered that trees are growing in its bed and developers have suggested building housing there. In the last 33 years, the Aral Sea has lost 50 percent of its surface area and 75 percent of its volume, with a concomitant tripling in its salinity, owing largely to diversion of water from its feeding rivers for irrigating cotton.[38]

A supply and demand graph helps to illustrate the inefficiency of subsidizing irrigation water even though its withdrawal and use have negative externalities. In Figure 20.8, the market equilibrium for irrigation water occurs where the marginal cost curve (MC) intersects the demand curve, resulting in a price of P_E and a quantity of Q_E. But suppose that irrigation is subsidized such that its price is P_S, below the equilibrium price. The quantity sold will increase from Q_E to Q_S.

In order to analyze the welfare effects, we also need to account for the negative externalities. The true marginal social cost of irrigation water is represented by the curve MSC, which includes the externality costs. For every unit above Q^*, the marginal social cost exceeds the marginal benefit (recall that the demand curve indicates the marginal benefits).

Area A represents the amount of net benefits of irrigation water at a quantity of Q^*. In other words, it is economically efficient to supply irrigation water up to Q^*. At the market equilibrium, Q_E, the net social welfare would be (A − B). At the subsidized quantity, Q_S, the net social welfare would be (A − B − C), a lower level of social welfare than at the market equilibrium. B and C represent areas of net loss resulting from a failure to internalize negative externalities and from subsidizing the price of water.

In this example, the maximum social welfare would be obtained at a quantity of Q^*. We could obtain this level of welfare by taxing water, as discussed in Chapter 3, instead of subsidizing it.

So far we have discussed water as if it has a single price. But the price of water varies in several respects. First, the price of water normally depends on its use. Specifically, water prices charged by utilities are different for domestic, agricultural, and industrial users. The cost of agricultural water in the United States is approximately \$5–\$100 per thousand cubic meters.[39] Meanwhile, a typical household monthly water bill is about \$20–\$120 per month, which equals a cost of about \$400–\$2,500 per thousand cubic meters.[40] While it may initially seem inefficient, and perhaps unfair, to charge different users different rates, there is some justification for charging agricultural and industrial users less than households. Household water requires a high degree of treatment because it must meet drinking water standards. Irrigation water is not required to meet the same quality standards and thus is cheaper to supply. After use, domestic water must also be removed for treatment. In many municipalities, households are charged a separate "sewer rate" for water disposal in addition to a charge for their water supply.

The price ranges presented above indicate that the price of water can vary regionally. Figure 20.9 shows the average monthly water bill in different American cities, presented in relation to average precipitation. We might expect that water prices would be highest where water is the most scarce (i.e., precipitation is the lowest). While some arid cities, such as Santa

Figure 20.8 Effects of Subsidizing Irrigation Water

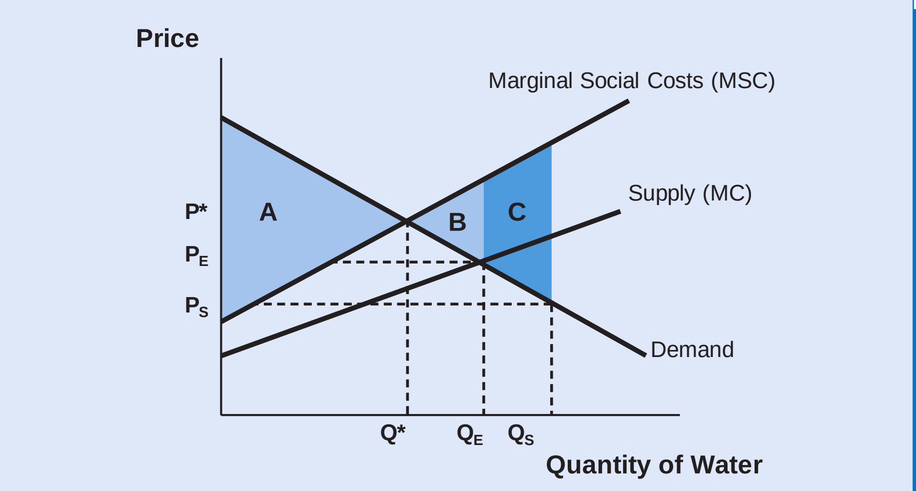
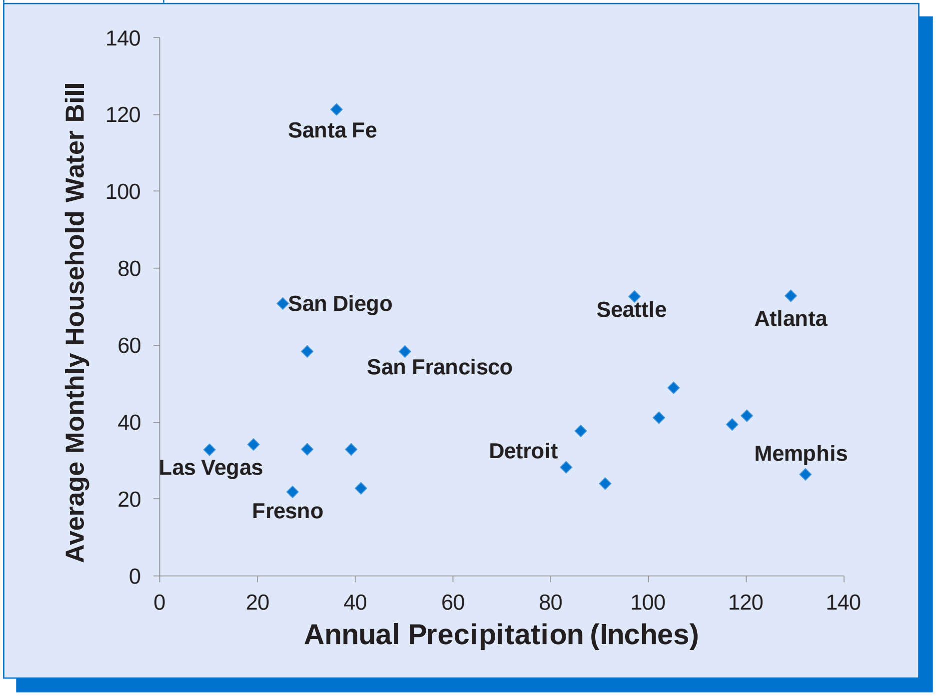


Figure 20.9 Average Monthly Water Bill versus Precipitation in U.S. Cities



Source: Walton, 2010.

Note: Water bill based on a family of four using 100 gallons per person per day. About 264,000 gallons is equivalent to a thousand cubic meters.

Fe and San Diego, do charge high water rates, other dry regions, such as Las Vegas and Fresno, charge very low rates. This reflects the kind of government subsidy for water discussed in the example above.

Water rates in relatively wet cities can also vary considerably. In fact, there seems to be no discernible relationship between water rates and precipitation. Of course, other factors can determine water availability besides precipitation. Water is relatively cheap near the Great Lakes because they provide a low-cost supply of water. Some cities may have access to sufficient groundwater while others may not. Some cities can store water in reservoirs to keep supplies relatively constant throughout the year.

Water prices are generally rising, particularly in regions where supplies are scarce and population is increasing. Additional supplies can often be obtained only by relying upon relatively expensive sources such as desalination. As water levels in underground aquifers fall, pumping becomes more expensive. As mentioned earlier, the alternative to obtaining additional supplies is to manage demand. By raising prices, utilities send consumers a signal about the increasing scarcity of water.

Higher water prices will induce a behavioral response in households and other water users. Irrigators are more likely to invest in efficient irrigation methods. Households are more likely to purchase low-flow showerheads and wash cars less frequently. But how much will water users reduce their water consumption in response to higher rates? This depends on the **price elasticity of demand**, as discussed in Chapter 3, Appendix 3.1. The elasticity of demand for

price elasticity of demand the responsiveness of the quantity demanded to price, equal to the percentage change in quantity demanded divided by the percentage change in price.

water tends to be inelastic, meaning that the percent change in the quantity demanded tends to be smaller in absolute value than the percent change in price.

A significant amount of research has been conducted to estimate the elasticity of demand for water, particularly for residential users. A 2003 meta-analysis identified more than 300 elasticity estimates from 64 studies.[41] The mean elasticity was –0.41, with a median of –0.35. A meta-analysis of studies on irrigation water found a mean elasticity of –0.51 and a median of –0.22, based on 53 estimates.[42] A review of several studies on industrial water use finds that the elasticity varies considerably across different industries, ranging from about –0.10 to –0.97.[43] As expected, water demand also tends to be more elastic in the long run than in the short run.

Based on these estimates, water managers can determine how to adjust the price to meet conservation objectives. For example, suppose that a water utility is experiencing a potential water shortage and needs to lower water usage by 10 percent: If the elasticity of demand is –0.41, then the water utility would need to raise price by 41 percent to achieve a 10 percent reduction in quantity demanded.

But the relationship between water demand and price is not as simple as this example. One reason is that elasticity is not constant across regions or seasons. In the meta-analysis of residential water mentioned above, water demand tends to be more elastic in arid Western states than in the eastern United States. Also, water demand tends to be less elastic in winter months than in summer months. In the summer, more water use is for relatively nonessential purposes, such as irrigating lawns and washing cars. In the winter, a higher percentage of total water use is for more essential tasks, such as bathing and washing dishes. So in the summer, households can more easily reduce water use in response to a price increase.

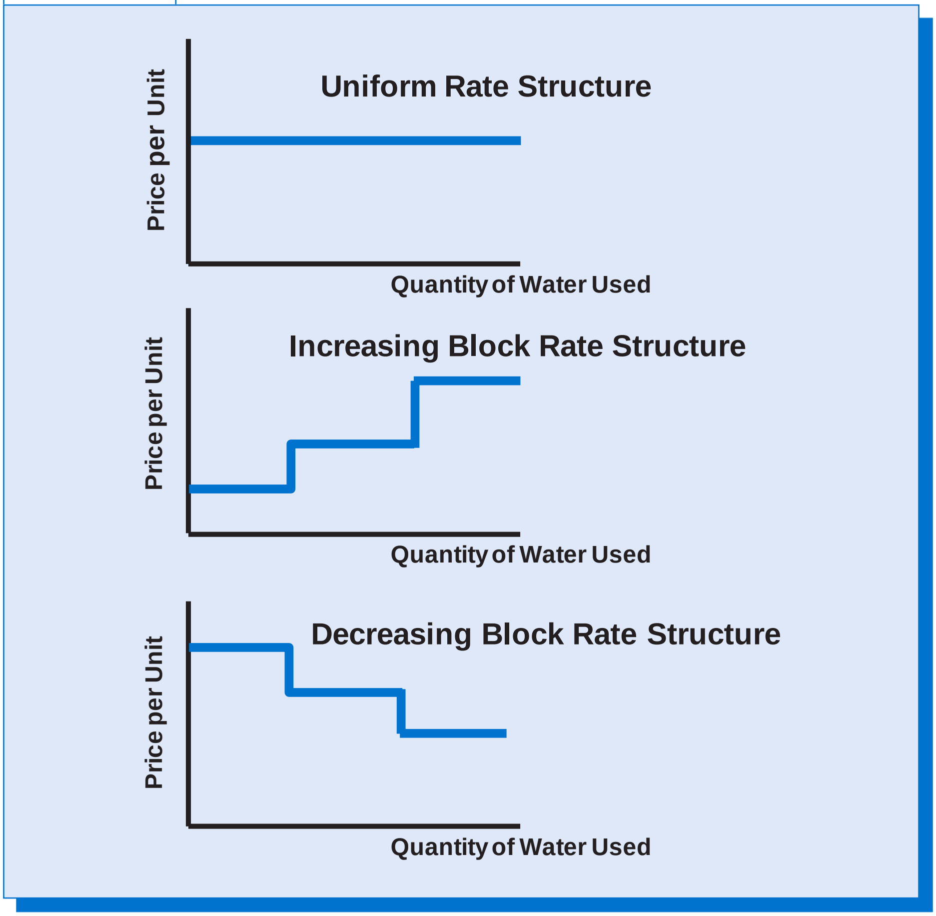
Another complication in pricing water is that water commonly is not sold at a constant price per unit. In some cases, water users simply pay a flat monthly fee and then are able to essentially consume all the water they wish with no marginal increase in cost. While water metering is standard in the United States, in some countries, including Canada, Mexico, Norway, and the United Kingdom, water is not normally metered.[44] Where water usage is metered, there are three basic pricing structures, as illustrated in Figure 20.10:

- **Uniform Rate Structure**: The price per unit of water is constant regardless of the amount of water used.
- **Increasing Block Structure**: The price per unit of water increases as the amount of water used increases. The price is constant within each block, but the price per unit is higher for successive blocks.
- **Decreasing Block Structure**: The price per unit of water decreases as the amount of water used increases.

An increasing block structure encourages more water conservation, as water users will wish to avoid moving into the higher-priced blocks. The rationale behind a decreasing block structure is that it provides a price break for large water users, typically for commercial or industrial users. Water may also be priced differently by season, with rates normally higher during the summer season to discourage nonessential water consumption.

In the past, decreasing block rate structures used to be the most common pricing method for public water supplies in the United States.[45] As concerns about water conservation have grown, increasing rate block structures have now become the most common approach. In 2008, 32 percent of U.S. public water systems used uniform rates, 28 percent used decreasing block rates, and 40 percent used increasing block rates.

Figure 20.10 Water Pricing Structures



Internationally, rate structures vary widely. An international survey of water utilities found that in OECD countries, 49 percent used increasing block pricing, 47 percent used uniform rates, and only 4 percent used decreasing block rates. In non-OECD countries, 63 percent of water utilities used uniform pricing, and nearly all others used increasing block pricing.[46] While an increasing block structure tends to promote higher rates of water conservation, other factors are also relevant when determining which rate structure and prices to adopt. Other considerations include:

- Utility rates are regulated; thus they cannot simply raise rates to induce a specific amount of conservation.
- Raising water rates disproportionately affects low-income households. Thus utilities may also try to take equity into consideration when setting water rates. In South Africa, the right to "sufficient water" is written into the constitution. This is operationalized by making the first block of water free (successive blocks are normally charged using an increasing block structure) so that even poor households can afford a baseline amount of water.

- Increasing block structures are somewhat more difficult to understand. Users should clearly understand when their usage moves into higher-priced blocks.
- Finally, raising water prices or changing the water rate structure may be politically difficult. While involving customers in rate discussions can increase support for conservation programs, utilities need to balance political feasibility with conservation objectives.

20.4 WATER RIGHTS, WATER MARKETS, AND PRIVATIZATION

An economically efficient distribution of water implies that water should be allocated toward uses that generate the highest marginal values (i.e., the highest willingness to pay). In theory, transferring water from low-valued uses to higher-valued uses increases overall social welfare. At the efficient allocation, the marginal value of water would be constant across different uses, such that further transfers would not clearly result in a net increase in overall welfare.

Table 20.3 provides estimates of the marginal value of water for several different uses, based on a review of existing studies from the mid-1990s in the United States. We see that the value of water can vary significantly among uses—highest for industrial and domestic uses, lowest for generating power and recreation/wildlife. The uses are not all mutually exclusive. For example, water could be used for recreation and then further downstream for irrigation.

The table suggests that there may be some potential for reallocating water from relatively low-valued uses to higher-valued uses. But we also need to account for differences in water quality. The marginal WTP for residential water would not be equal to the marginal willingness to pay for irrigation water at the efficient allocation because the water quality needs of these users differ.

riparian water rights a system of water rights allocation based on adjacent land ownership.

In general, the allocation of water in the United States and elsewhere is rarely determined by concerns about economic efficiency. Instead, water rights are usually allocated based on various historical and legal considerations. In the eastern United States, water rights are commonly allocated based on **riparian water rights**. Under this doctrine, the right to reasonable use of water is granted to

Table 20.3 Marginal Value per Acre-Foot of Water in Various Uses

Water Use	Average Value per AF	Median Value per AF
Navigation	$146	$10
Recreation/Wildlife Habitat	$48	$5
Hydropower	$25	$21
Thermoelectric Power	$34	$29
Irrigation	$75	$40
Industrial	$282	$132
Domestic	$194	$97

Source: Frederick *et al.*, 1996.

Note: A large difference between the average and median values indicates that a relatively small number of particularly large estimates shifts the average upward.

those who own the land adjacent to a water source. Where demands exceed the available water supply, rights may be allocated based on the amount of water frontage of each owner. Riparian water rights generally do not allow for irrigation withdrawals or the transfer of water to lands nonadjacent to bodies of water.

While riparian water rights were initially applied in the western United States, by the late 1800s the water demands of agriculture and mining necessitated a different water rights system. **Prior appropriation water rights** separate the right to water from land ownership. Under this system, a right to water is recognized when someone establishes a **beneficial use** for it, such as for irrigation or municipal use. This system is also called "first in time, first in right" because rights are assigned on the basis of when a beneficial use first occurs.

prior appropriation water rights a system of water rights allocation in which rights are not based on land ownership but on established beneficial uses.

beneficial use term used to refer to the use of water for productive purposes, such as irrigation or municipal supplies.

Say, for example, that a farmer begins to withdraw 1,000 AF of water per year from a river. Then suppose that several years later a factory wishes to withdraw 5,000 AF per year from the same river. The farmer would be recognized as the "senior appropriator," and the factory (the "junior appropriator") would only have access to water after the farmer takes 1,000 AF. Anyone else who starts to withdraw water after the factory has established its right could still establish a prior appropriation right, but only after both the farmer and factory have taken their full allotment. In the case of a drought, if only 3,000 AF were available from the river, the farmer could get his or her full allocation of 1,000 AF, the factory would get the remaining 2,000 AF, and any other more-junior water users would get nothing.

Obviously, the doctrine of prior appropriation does not allocate water in an economically efficient manner. In fact, it tends to discourage conservation because if senior water right holders start using less than their full allocation, over time the amount of water associated with their rights could be legally reduced. Also, prior appropriation rights tend to make no allowance for ecological needs. Thus in the case of water shortages, ecosystems may suffer significant damage.

The creation of **water markets** has been proposed as a way to increase the economic efficiency of water allocation in the presence of prior appropriation rights. In a water market, water rights holders can sell some of their water to willing buyers. One example is a farmer who sells some of his or her water to a municipality. The municipality might buy the water in a one-time purchase (referred to as a lease) or could buy the actual water rights, which would establish it as the senior appropriator for a given amount of water per year.

water markets mechanism to sell water or water rights to potential buyers.

As in any other market transaction, a water market in theory increases social welfare because both the buyers and sellers perceive that they will benefit from the transaction. But efficiency gains may need to be weighed against the impact of water markets on existing inequities. If poor people hold secure water rights, then water markets could provide an additional source of income. More likely, though, is that water could be directed away from the needs of the poor toward profitable uses by large-scale farmers, corporations, or other interests. For example, water markets were established in Chile in the early 1980s but led to higher water prices as a result of speculation and the monopolization of water rights. In 2005 the Chilean water market laws were revised to limit the potential for speculation and monopolization.

A water market does not necessarily require the direct transportation of water. An upstream water right holder could easily sell her rights to a downstream user. The upstream right holder would simply withdraw less water, allowing the downstream user to withdraw more. The sale of a water rights from a downstream user to an upstream user could also be conducted similarly. But in some cases a water sale may require water to be transported through canals or pipes.

A fairly complex system for water transfers has already been established in the western United States. The California State Water Project and the Central Arizona Water Project are examples of engineering projects that transport water hundreds of miles to its final users.

The conditions necessary for a successful water market to form have been identified as:

- Water rights must be clearly defined.
- Water demand must exceed water supply. There must be some water users or potential users who are unable to obtain all water they seek at prevailing prices.
- Water supplies must be transferable to where water is desired for purchase and available when it is needed. Also, transaction costs must be relatively low.
- Water buyers must be confident that purchase contracts will be honored, with appropriate regulation and oversight.
- A system must be in place to resolve conflicts. This could involve both legal proceedings and less-formal resolution options.
- The cultural and social context must be considered. Some regions may resist water markets if most people believe that water is not a salable commodity.[47]

Water markets are in place in several countries, including Australia, Chile, South Africa, the United Kingdom, and the United States. An analysis of water markets in the United States identified about 1,400 water sales between 1990 and 2003.[48] Most of the water volume transferred involved short-term leases rather than outright purchases of water rights. Municipalities were the most common purchaser of water (normally from irrigators), but transfers between irrigators were also common.

About 17 percent of the water purchased was for environmental purposes, including purchases by municipalities and environmental organizations. The potential for water market transfers to meet environmental objectives, such as maintaining sufficient in-stream flows for wildlife habitat, is receiving increased attention. Some analysts see great potential for water markets to improve the environment:

> Overcoming [barriers to water market trades] is an increasingly important challenge as populations and western economies continue to grow. With this growth comes increasing demands for environmental and recreational amenities. . . . Removing barriers to trade will reduce transaction costs, promote more efficient water allocation among offstream and instream uses, create incentives for improved water use, and improve environmental quality.[49]

Even where environmental values exceed the values of other water uses, the proper institutions must exist to obtain the necessary funding. The problem is similar to our public goods discussion in Chapter 4. Voluntary contributions to environmental organizations can raise some funds to purchase water rights, but the presence of free riders means that environmental water purchases will be undersupplied to society. Also, water markets can harm as well as help the environment. Water transfers can degrade water quality and excessively deplete aquifers.[50] And as in any market, negative externalities may require government intervention to internalize the externalities.

Water Privatization

A related issue is whether water should be supplied as a public good by government agencies or as a commodity by private companies. **Water privatization** has been promoted by international organizations such as the World Bank and International Monetary Fund on the grounds that private companies can provide more efficient and reliable service than public entities, particularly in developing countries. In theory, if a private company can provide water at a lower cost, then these cost savings can be passed on to customers, and perhaps more people can obtain access to water. But without appropriate regulation a private company may be able to charge excessive rates or fail to address the water needs of low-income households.

water privatization the management of water resources by a private for-profit entity as opposed to a public utility.

Water privatization has occurred, to some extent, in many countries, including Brazil, China, Colombia, France, Mexico, and the United States. The experience with water privatization has been mixed. According to the World Bank, water privatization in Manila, Philippines, has been successful in expanding water supplies to poor households:

> By expanding the provision of reliable and affordable services to customers, the program has benefited some 107,000 poor households since its inception in 1997. Near-to-regular access to potable/piped water supplies and increased community sanitation facilities has been achieved in low-income residential centers. Furthermore, the program established customer facilities to encourage communities to discuss and participate in the process of expanding services, and to resolve their concerns.[51]

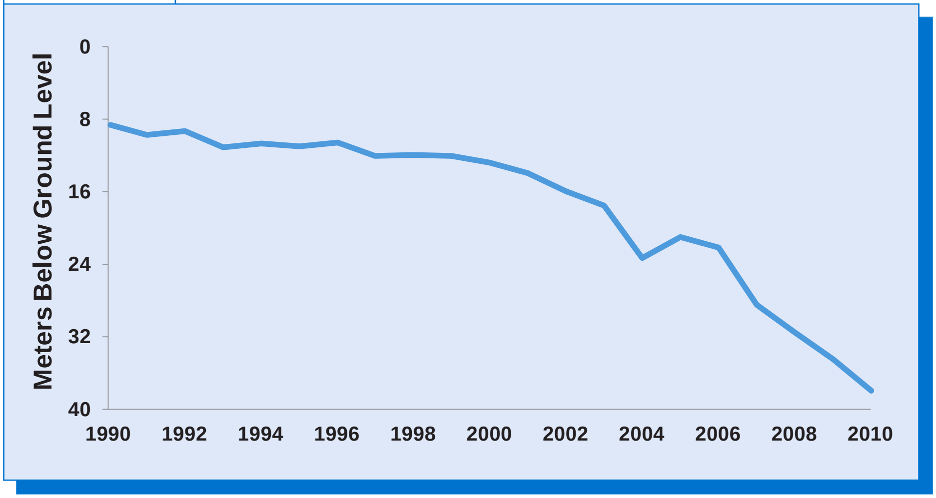
However, in other cases water privatization has failed to deliver on its promise. A dramatic example was the experience in Bolivia.

> In April 2000, after seven days of civil disobedience and angry protest in the streets, the president of Bolivia was forced to terminate the water privatization contract granted to Aguas del Tunari, subsidiary of the giant Bechtel corporation. The Bolivian government had granted a 40-year contract to Aguas del Tunari in 1999. . . . Water rates increased immediately—by 100 to 200 percent in some cases. Small farmers and the self-employed were especially hard hit. In a country where the minimum wage is less than $100 per month, many families were paying water bills of $20 or higher.[52]

The privatization of water resources can also lead to their overexploitation. In many rural communities throughout the world, access rights to groundwater have been sold to soft-drink producing companies such as Coca-Cola and Nestlé. These multinationals have often exploited the water resources in unsustainable ways, such as in the village of Plachimada, in the State of Kerala, India. Not long after Coca-Cola started its bottling plant, pumping out groundwater, farmers found that groundwater was contaminated and toxic waste released. Popular resistance eventually led to the shutdown of operations at the plant.[53] In another rural town in India, Kala Dera, scientists have measured a dramatic decline in the groundwater table after a Coca-Cola bottling plant started its operations in 2000, as seen in Figure 20.11.

The World Bank continues to promote privatization, noting that higher water prices are necessary to induce conservation. Public utilities rarely charge enough to reflect the true economic and social costs of water, which privatization advocates argue is the root cause of unsustainable water use. From the perspective of social welfare, even market prices are too low if they fail to account for externalities. But economic efficiency may conflict with the goal of equity. Privatization may work best when combined with policies ensuring that the poorest can afford enough water to meet their basic needs, as in the South African system that provides a basic supply of water for free, with increasing prices for larger quantities.

Figure 20.11 Groundwater Levels Before and After Coca-Cola Started Operations in 2000 in Kala Dera, India, 1990–2010



Source: India Resource Center, http://www.indiaresource.org/news/2011/1008.html.

Note: A Coca-Cola bottling plant started operations in 2000, leading to a dramatic decline in groundwater levels.

Box 20.4

THE NEW OIL: SHOULD PRIVATE COMPANIES CONTROL OUR MOST PRECIOUS NATURAL RESOURCE?

There is wide agreement that global water supplies are being used unsustainably. Can privatization lead to more sustainable practices, with market prices motivating water conservation?

Privatization of water supplies has traditionally been implemented in developing countries. In the late 1990s the World Bank pushed scores of poor countries to privatize their water supplies as a condition for receiving desperately needed economic assistance. In several cases, most infamously Bolivia, private companies raised the price of water so much that poor families couldn't afford enough to meet basic needs.

But more recently emphasis has shifted to privatizing water in richer countries. "These are the countries that can afford to pay," says water rights attorney James Olson. "They've got huge infrastructure needs, shrinking water reserves, and money."

The need for better water management is especially acute in China. As groundwater demands increase in Beijing, wells dug around the city must reach ever-greater depths (nearly two-thirds of a mile or more, according to a recent World Bank report) to hit fresh water. With contracts to supply water becoming more lucrative, the number of private water utilities has skyrocketed. But in order to recover investment costs, companies have dramatically raised the price of water. "It's more than most families can afford to pay," says Ge Yun, an economist with the Xinjiang Conservation Fund. "So as more water goes private, fewer people have access to it."

Source: Interlandi, 2010.

Water markets and privatization remain controversial. The challenge is to ensure that markets and privatization operate in a manner to meet broader social and environmental goals, rather than simply maximize profits. (For more on this debate, see Box 20.4.) A major problem with privatization is that it fails to recognize the nature of water as a common property resource, discussed further in the next section.

20.5 WATER AS A COMMON PROPERTY RESOURCE

Although the World Bank and other international financial institutions are still promoting privatization, community opposition has pushed policy in many areas in the opposite direction, of re-municipalization of water supplies:

> A report by the Transnational Institute (TNI), Public Services International Research Unit and the Multinational Observatory indicates that 180 cities and communities in 35 countries, including Buenos Aires, Johannesburg, Paris, Accra, Berlin, La Paz, Maputo and Kuala Lumpur, have all "re-municipalized" their water systems in the past decade. More than 100 of the "returnees" were in the US and France, 14 in Africa and 12 in Latin America. Those in developing countries tended to be bigger cities than those in richer countries."[54]

Remunicipalization can improve access and quality of water services, and also offers opportunities to build democratic governance, by involving citizens into the collective decision-making processes, strengthening accountability and transparency. It pressures municipalities to be more responsive to the needs of the poorest of their inhabitants, in ensuring a basic right to water, which a purely market-based approach to water management may not.

Municipal control is one approach to the management of water as a common property resource. Another approach is traditional communal management. As discussed in Chapter 4, there is a long history of management of common property resources through communal institutions. This is true of water resources in many areas. Local collective systems of irrigation that have proved sustainable over centuries are found in numerous societies around the world (see Box 20.5).

In an effort to emulate the benefits of traditional communal water management systems, some hydrologists have proposed a new paradigm of water management, **watershed restoration**, based on small scale natural water cycles. Through the careful harvesting of rainwater, which is then used to recharge groundwater, and through the re-creation and protection of wetlands that purify water and retain it in the soils, natural water cycles can be restored. Rethinking water cycles as part of the larger ecosystem picture implies a different approach to water management in the future. As part of this new paradigm, the role that water cycles play in mitigating climate change can be recognized and enhanced. Recreating local wet ecosystems and restoring small-scale water cycles can help combat some of the worst effects of climate change by increasing mist and moisture in the atmosphere, preventing drying and desertification.[55]

> **watershed restoration** restoring natural watershed functions through the management of small-scale water cycles.

Exploring different approaches to water management reflects the dual nature of water as both private and public good. No single approach is likely to hold the answer, but a balance of considerations of ecological cycles, economic efficiency, and the social functions of water is clearly needed.

Box 20.5
THE ACEQUIA WATER SYSTEM

The Acequia water management system evolved over 10,000 years in the deserts of the Middle East (the name derives from "as-saaqiya" which means "water conduit" in Classical Arabic), and was introduced into Southern Spain by the Moors. Spanish colonizers took acequias to the New World, where they found similar ancient indigenous systems of collective irrigation that Native Americans had developed for centuries. Acequia agroecosystems promote soil conservation and soil formation, provide terrestrial wildlife habitat and movement corridors, protect water quality and fish habitat, and support crop biodiversity. Acequias have been maintained through a carefully regulated and monitored collective management of common-property resources, reinforcing a strong land and water ethic.

The non-monetary services offered by traditional community-based systems of acequias in the Upper Rio Grande Bioregion include ecosystem services as well as social and cultural services, such as spiritual and religious values, educational values, and esthetic values, which greatly enhance the quality of life of the communities which take care of these agroecosystems. In recent times these traditional systems of common property resource management, which were based on bartering systems where irrigators/neighbors would exchange services with one another, are experiencing the pressures of the dominant monetary market economy in ways that disrupt the ancient customs and communal practices. Market pressures have led some to sell their rights to bigger interests, such as the City of Las Vegas. But market mechanisms may not be the best way to allocate scarce water rights, since transfer of water rights to the highest bidder may be unfairly coercive for cash-poor people.

Sources: Elinor Ostrom, 1990, p. 69–82; Nejem Raheem, 2014, "Using the Institutional Analysis and Development Framework to Analyze the Acequias of El Rio De Las Gallinas, New Mexico," *The Social Science Journal*, http://dx.doi.org/10.1016/j.soscij.2014.02.004.

Summary

Water systems are under pressure from steadily growing agricultural, industrial, and urban demand. Many countries currently experience permanent water stress, defined as less than 1,700 cubic meters per capita available supply. Shortages will become more serious as population grows and climate change affects precipitation patterns and glacial runoff. Human activity relies on water consumption as a fundamental input. The concept of virtual water takes into account both direct and indirect uses of water to create goods and services. This concept can be used to calculate a "water footprint" for an individual, community, corporation, city, or country. Trade in virtual water allows water-scarce countries to import goods that are water-intensive, but some water scarce countries are depleting their scarce water resources through water-intensive exports.

Increasing supply by pumping from aquifers has led to groundwater overdraft in major water-scarce areas throughout the world. Construction of dams also increases available supply, but most major dam sites are already being exploited, and new dam construction often involves major environmental and social costs. Desalination offers the potential to tap into a virtually unlimited supply of ocean water, but it is energy intensive and expensive. Innovative methods of collecting rainwater and protecting watersheds and waterways offer a new paradigm of water management, which restores natural processes of replenishment of local water cycles.

Proper water pricing can promote conservation and encourage technologies for efficient water use. Government policies, however, often subsidize water, thereby encouraging overuse.

Higher prices will reduce demand, but since water demand is inelastic, relatively large price increases are necessary to induce significant conservation. Well-designed price structures, such as increasing block pricing, can also promote conservation.

In theory, water markets can increase the economic efficiency of water allocation by allowing transfers from low-valued uses to higher-valued uses. Water markets can also be used to meet environmental objectives, although the results have been mixed. Privatization of water supplies has also produced mixed results, expanding affordable access in some situations while leading to dramatic price increases and reduced access in other cases. The evidence indicates that while both the private and public sectors have a role to play in meeting water challenges, appropriate regulation and institutions are needed to ensure that water is sustainably managed. These institutions can include management of water both as a marketed and as a common-property resource.

Key Terms and Concepts

absolute water scarcity
average-cost pricing
beneficial use
desalination
flow
hydrologic cycle
micro-irrigation
price elasticity of demand
prior appropriation water rights
regulated monopolies
riparian water rights
stock
virtual water
water footprint
water markets
water pricing
water privatization
water scarce
water stressed
watershed restoration

Discussion Questions

1. Suppose you were managing a public water utility facing a shortage due to drought conditions. What steps would you take in response to the drought?
2. Human demands for water can lead to an insufficient supply for maintaining natural resources such as wetlands and fish habitat. How would you balance the allocation of water between human and environmental demands?
3. Do you believe that access to safe drinking water is a fundamental human right? How should water be priced in developing countries, considering the potentially conflicting issues of affordability and conservation?

Notes

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25. http://wwf.panda.org/what_we_do/footprint/water/dams_initiative/quick_facts/. Large dams are defined as those over 15 meters in height.
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28. WaterReuse Association, 2012.
29. Equinox Center, 2010.
30. Elimelech and Phillip, 2011, 712.
31. Postel, 1992, chap. 8.
32. Equinox Center, 2010, p. 18.
33. Olmstead and Stavins, 2007.
34. See Hanemann, 2005, for a discussion of the value and price of water.
35. Recall the discussion of use and nonuse values in Chapter 6.
36. See Carter and Milton, 1999.
37. Wichelns, 2010, p. 7.
38. Strockel, 2001, pp. 4–5.
39. Wichelns, 2010.
40. Walton, 2010.
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42. Scheierling *et al*., 2004.
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48. Brown, 2006.
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50. Chong and Sunding, 2006.
51. World Bank, 2010, p. 2.
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Web Sites

1. **www.epa.gov/environmental-topics/water-topics.** The U.S. Environmental Protection Agency's water portal, with links to information about watershed protection, oceans, drinking water, and freshwater.
2. **www.unesco.org/new/en/natural-sciences/environment/water/wwap/wwdr/.** Web site for the United Nations' World Water Development Report, published every three years. Current and past reports can be freely downloaded.
3. **www.fao.org/nr/water/.** The Food and Agriculture Organization's water portal, with reports and links to a database of water information.
4. **www.waterfootprint.org/en/resources/interactive-tools/national-water-footprint-explorer/.** Water Footprint Network's National Water Footprint Explorer, showing water footprints for each country and each person in a country.

PART VI

Environment, Trade, and Development

CHAPTER

21

World Trade and the Environment

Chapter 21 Focus Questions

- What effects does expanded trade have on the environment?
- Should regional and global trade agreements include environmental protection?
- What policies can promote sustainable trade?

21.1 ENVIRONMENTAL IMPACTS OF TRADE

Nearly 30 percent of global economic production is traded across national boundaries.[1] As world trade has expanded in recent decades, the relationship between trade and the environment has received increasing attention. Is trade good or bad for the environment? How will trade affect the exporting country, the importing country, and the world as a whole? Who is responsible for responding to environmental problems associated with trade? The answers to these questions are sometimes complex, and economic theory can help us to understand the social and environmental implications of trade policy.

International attention first focused on these issues in 1991, when the Mexican government challenged a U.S. law banning tuna imports from Mexico. The U.S. Marine Mammal Protection Act prohibited tuna-fishing methods that killed large numbers of dolphins and banned tuna imports from countries, including Mexico, that used such fishing methods. The Mexican government argued that the U.S. prohibition on Mexican tuna imports violated the rules of the **General Agreement on Tariffs and Trade (GATT)**.

Created in the 1940s, the GATT was an international agreement to reduce tariffs and other barriers to trade. The GATT was replaced in 1995 by the **World Trade Organization (WTO)**, which we will discuss in more detail later in the chapter. According to the free-trade principles that provided the basis for the GATT, and later for the WTO, countries could not restrict imports for environmental reasons except in limited cases such as protecting the health and safety of their own citizens. A GATT dispute panel ruled that the United States could not use domestic legislation to protect dolphins outside its own territorial limits, and thus could not prohibit imports of tuna from Mexico. Although Mexico did not press for enforcement of this decision, the tuna/dolphin decision opened a major controversy over issues of trade and environment.

General Agreement on Tariffs and Trade (GATT) a multilateral trade agreement providing a framework for the gradual elimination of tariffs and other barriers to trade; the predecessor to the World Trade Organization.

World Trade Organization (WTO) an international organization dedicated to the expansion of trade through lowering or eliminating tariffs and nontariff barriers to trade.

This debate has expanded to cover many international environmental issues, including forest protection, ozone depletion, hazardous wastes, and global climate change. All these issues are linked, to some extent, to international trade policies. If individual countries are prohibited from using trade measures to protect the environment, as in the tuna/dolphin case, then international trade law seems to favor expansion of trade over environmental quality. On the other hand, international agreements on trade can also be structured so as to promote environmental goals.

At the national level, the standard economic policy response to environmental impacts is to implement policies that internalize externalities, as discussed in earlier chapters. At the international level, however, the picture is more confusing. The burden of environmental externalities associated with trade may be borne by importers, exporters, or by others not directly involved in producing or consuming traded goods. The authority to formulate and enforce environmental policies usually exists only at the national level. This can create significant problems when environmental impacts are transnational, because provisions for environmental protection in most international trade agreements are often weak or nonexistent, as we'll discuss later in the chapter. To address these issues, we first turn to an examination of the basic economic theory relevant to the trade/environment nexus, combining elements of the standard economic theory of trade with the theory of environmental externalities.

Comparative Advantage and Environmental Externalities

A basic principle of standard economic theory is that expanded trade is generally beneficial, promoting increased efficiency and greater wealth among trading countries. Known as the theory of **comparative advantage,** this analysis demonstrates that two trading countries will both gain by specializing in producing those goods and services that they can produce most efficiently, and then trading with each other. Both countries will be able to achieve a consumption level that is unattainable without trade. But what if expanded trade causes environmental damage? How will this affect the analysis of costs and benefits from trade?

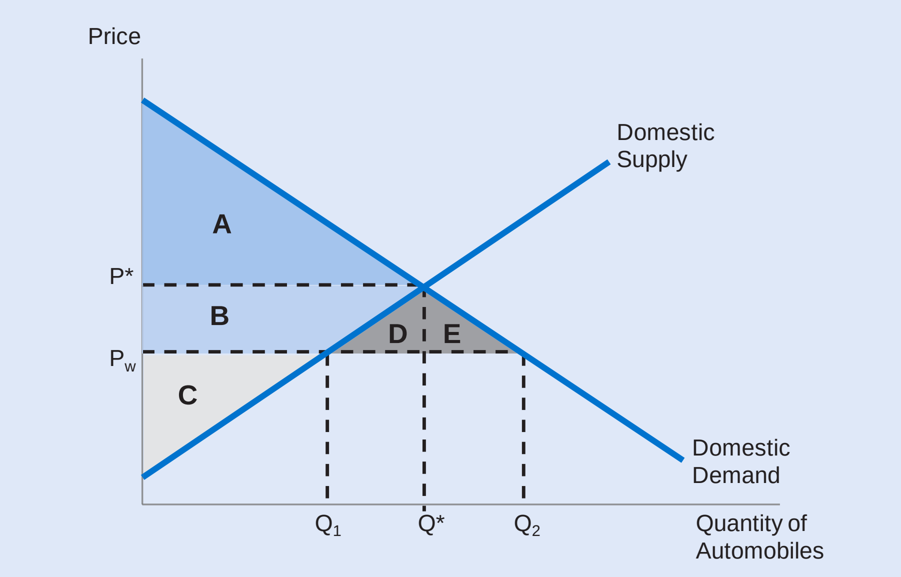
comparative advantage the theory that trade benefits both parties by allowing each to specialize in the goods that it can produce with relative efficiency.

We can use economic welfare analysis, introduced in Chapter 3, to analyze the gains and losses associated with the environmental effects of trade. We start by introducing a graphical welfare analysis of trade without considering the environmental externalities created by producing and consuming goods and services. Consider Figure 21.1, which uses automobiles as an example of an imported good's welfare effects on consumers and producers.

In the absence of trade, domestic supply and demand would be in equilibrium at a quantity of Q^* and with a domestic price of P^*. We can obtain the welfare in this automobile market as the sum of consumer and producer surplus. Consumer surplus would be area A and producer surplus would be areas $(B + C)$; thus, total welfare without trade is $(A + B + C)$.

Now let's assume this country can trade, and becomes an importer of some automobiles. With trade, both production and consumption of automobiles will change in this importing country. If there are no barriers to trade, automobiles can be imported at the world price P_w, which is typically lower than the domestic market price for the good. (We assume for this example that the country's demand is not large enough to affect the world price.)[2] With prices forced down to P_w by competition from relatively cheap imports, domestic producers are only willing to produce Q_1 automobiles. But at this lower price, the quantity of domestic

Figure 21.1 Gains and Losses from Importing Automobiles



demand has increased to Q_2. The difference between Q_2 (demand) and Q_1 (domestic supply) indicates the quantity of imported automobiles. The resulting equilibrium is at a price of P_w and a quantity of Q_2.

How does trade affect domestic economic welfare? With a lower price and a higher quantity consumed, consumer surplus increases from area A without trade to $(A + B + D + E)$. But producer surplus decreases to area C, as domestic producers only sell Q_1 automobiles at a price of P_w. Total social welfare with trade is $(A + B + C + D + E)$, larger than the previous social welfare without trade of $(A + B + C)$. The net gain as a result of trade is the triangular area $(D + E)$. This essentially demonstrates the basic theory of comparative advantage, showing clear gains from trade. (Note that these are overall gains to the country; some groups can lose from trade, such as domestic auto workers who may lose their jobs when the industry contracts. The theory of comparative advantage says only that overall gains are larger than losses.)

But this basic theory leaves out any environmental externalities associated with trade. In Chapter 3 we did not address whether the externalities associated with a particular good were a result of the production or the consumption of the good. But now we need to differentiate between **production externalities**, caused by automobile production, and **consumption externalities**, resulting from automobile use (e.g., burning gasoline) and eventual disposal. As we did in Chapter 3, production externalities can be represented as an additional cost to the private supply curve. This is shown in Figure 21.2, with the social cost of supply given by S'. Note that the externalities associated with the production of the *imported* automobiles are not shown in this graph, as we are only considering welfare impacts in the importing country for now. (We will consider the environmental impacts associated with exporting in another example.)

production externalities externalities associated with the production of a good or service, such as emissions of pollutants from a factory.

consumption externalities externalities associated with consumption of a good, such as pollutant emissions from vehicles.

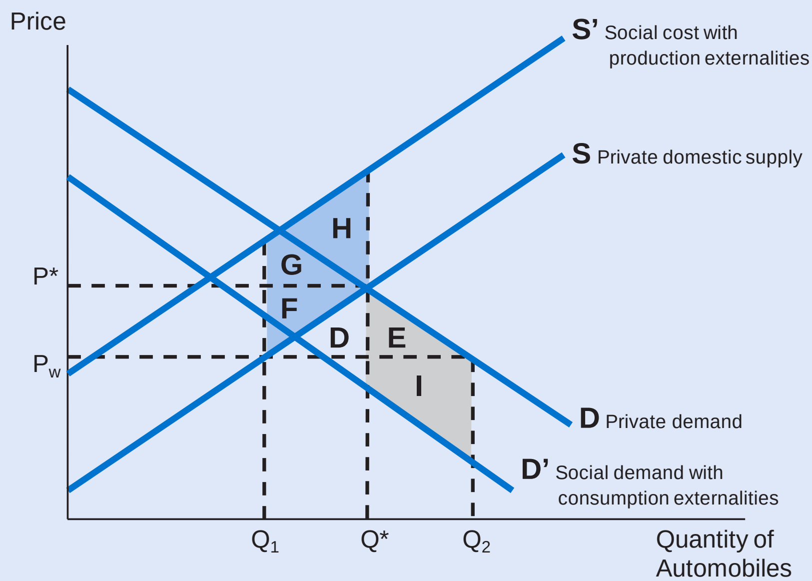
As in Chapter 3, the welfare effects of a negative production externality can be represented by a parallelogram between S and S' up to the quantity of automobiles produced domestically. Prior to trade, this parallelogram would have extended up to Q^*. But with trade, and lower domestic production, the negative production externality only extends up to Q_1. Thus trade results in lower production externalities, by areas $(F + G + H)$—the blue-shaded region in Figure 21.2. So in addition to the gains from trade accruing to market participants, areas $(D + E)$, the reduction in production externalities also provides a welfare gain.

But we also need to consider consumption externalities. The total quantity of automobiles sold increases from Q^* to Q_2 with trade. So we will have more air pollution from burning gasoline, more oil runoff into streets, more highway congestion, a greater contribution to global carbon emission, and more vehicles entering the waste flow once their useful life is over. These additional consumption externalities will, at least to some extent, offset the welfare gains from lower domestic production externalities.

To present consumption externalities in our graph, first recall that a demand curve represents the marginal benefits of consumers. But with the presence of consumption externalities the social benefits associated with automobile consumption are lessened. Just as we added production externalities as an additional social cost to the private supply curve, we can subtract consumption externalities from the private benefits to obtain the true social benefits of automobiles.

So in Figure 21.2 we subtract the consumption externalities from private demand to obtain curve D'—the social marginal benefits of automobile consumption. Consumption externalities would be represented by the parallelogram between D and D', up to the quantity

Figure 21.2 Welfare Impacts of Importing Automobiles with Externalities



of automobiles consumed. Prior to trade, this parallelogram would have extended to *Q**. But after trade it extends further, to Q_2. So the increase in consumption externalities as a result of trade would be areas *(E + I)* in the graph—the gray-shaded region.

We can finally assess the overall welfare effects of trade in this country, based on the three factors: the change in market benefits, the reduction in production externalities, and the increase in consumption externalities. The net welfare effects are:

$$\text{Net change in welfare} = (D + E) + (F + G + H) - (E + I)$$
$$= (D + F + G + H) - I.$$

Before we considered environmental externalities, trade unambiguously provides net welfare gains. Now, whether trade actually increases net welfare or not depends on whether *(D + F + G + H)* is greater than area *I*. The way we have drawn Figure 21.2, it appears that *(D + F + G + H)* is significantly greater than *I*, and trade results in net benefits even with consideration of externalities. But this need not always be the case. In the case of automobiles, we might find that the consumption externalities per vehicle far exceed the production externalities. This would increase the size of area *I* relative to areas *(F + G + H)*, and possibly result in trade lowering overall social welfare in the importing country.

Our results have important implications for trade theory. In the basic trade case without externalities, we can unambiguously claim overall **gains from trade**. Even though one group (automobile producers) loses, consumer gains outweigh these losses. After we introduce externalities, however, we can no longer be so sure of net gains from trade, as it depends on the size of the production and consumption externalities. Policy actions by an importing country, such as a tax on automobile use, could internalize these external costs, but unless we know that such policies will be implemented, we cannot be sure of a net gain from trade.

gains from trade the net social benefits that result from trade.

Exports and Environmental Externalities

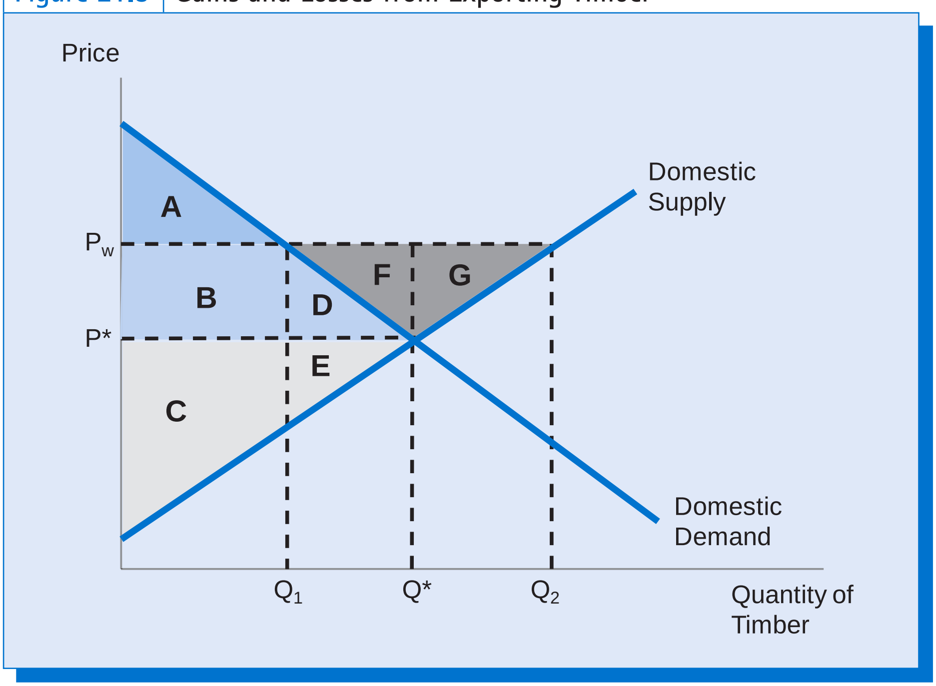
We now turn our attention to the welfare effects of trade on an exporting country. Again we will start with a welfare analysis of trade in the absence of externalities, and then consider how consideration of environmental impacts changes social welfare. Here we use timber exports from a developing country as our example, as shown in Figure 21.3.

In the absence of trade, the domestic price of timber is P^* and the quantity of timber sold is Q^*. Consumer surplus is $(A + B + D)$ and producer surplus is $(C + E)$. Now suppose the country can export timber, and that the developing country can get a higher price for its timber on the world market, which includes demand from richer nations. Given access to world markets and a higher price of P_w, timber suppliers in the country will raise their domestic prices to P_w as well. In other words, suppliers will no longer be willing to sell to domestic consumers at the former domestic price of P^*, because they can always export their timber at a price of P_w.[3]

Faced with a higher price, domestic consumers reduce their timber purchases to Q_1. Thus consumer surplus declines to area A. At a price of P_w suppliers are willing to sell a quantity of Q_2. The difference between Q_1 and Q_2 represents the amount of timber that is exported. As a result of greater sales at a higher price, producer surplus increases from $(C + E)$ to $(B + C + D + E + F + G)$. The gain in producer surplus $(B + D + F + G)$ more than offsets the loss of domestic consumer surplus $(B + D)$, for a net social gain of areas $(F + G)$. Once again, the theory demonstrates overall gains from trade without considering environmental externalities. (And once again, there can be some losers from trade, in this case domestic consumers).

As you might guess, the situation is not so unambiguous when we introduce the externalities of timber production—which include land and watershed degradation as well as reductions in use and nonuse values. These production externalities are shown in Figure 21.4, represented by the difference between the private supply curve and the social cost curve S', which shows the production costs plus environmental externalities. Prior to trade, the

Figure 21.3 Gains and Losses from Exporting Timber



production externalities of timber would have been a parallelogram between these two curves extending up to a quantity of Q^*. With trade and expanded production, these externalities extend further, up to Q_2. Thus the increase in production externalities is area $(G + H)$. There could also be changes in consumption externalities associated with lower domestic consumption of timber, but since these are probably much less significant than in the case of automobiles, we omit them from Figure 21.4.

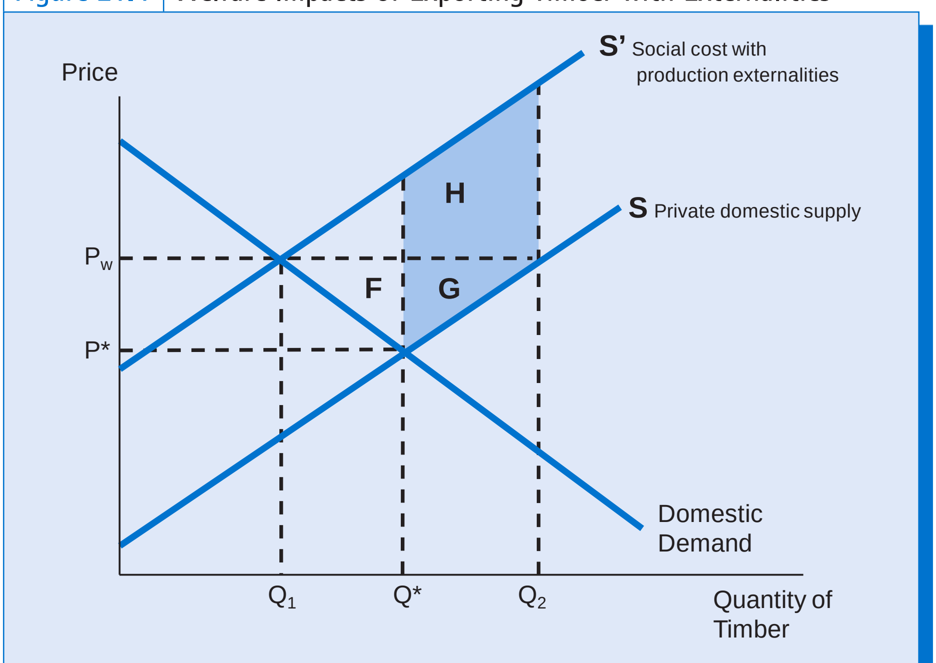
Taking into account these environmental externalities, we cannot say unambiguously that there are net benefits from trade to this exporting country. Market benefits have increased by $(F + G)$ but externalities have increased by $(G + H)$. The net change in welfare is $(F - H)$. If area F is greater than area H, then there will be a net social gain from trade, but if area H is greater than area F there will be a net loss. As we've drawn Figure 21.4, there appears to be a net loss of welfare, implying that in this case the environmental damages from timber production outweigh the net commercial gains from trade. As with the earlier example of imports, whether there is a net benefit or loss for any specific export will depend on the size of the different trade and environmental effects.

Our examples, of course, represent a very simple model of trade, but the conclusion that environmental costs may seriously affect net gains from trade is far-reaching. In the real world, countries trade trillions of dollars' worth of products. Where there are significant environmental externalities, trade will reallocate these externalities among countries, and may increase externalities overall due to expanded production.

exported emissions/pollution shifting the impacts of pollution to other countries by importing goods whose production involves large environmental impacts.

One implication of this analysis is that it may be possible to **export pollution** by importing goods whose production creates heavy environmental impacts, effectively shifting these emissions to other countries. (It is often the case that pollution is exported from

Figure 21.4 Welfare Impacts of Exporting Timber with Externalities



developed to developing countries, as we'll discuss later in the chapter.) Trade also necessarily involves energy use for transportation, with resulting air pollution and other environmental consequences such as introduction of alien invasive species.[4] Indirect effects of trade might also occur, for example when larger-scale export agriculture displaces peasant farmers onto marginal lands such as hillsides and forest margins, leading to deforestation and soil erosion. Specific kinds of trade, such as trade in toxic wastes or endangered species, can have obvious negative environmental impacts.

Trade can also have some environmentally beneficial effects. Freer trade may help spread environmentally-friendly technology. Trade tends to promote more efficient production, which reduces materials and energy use per unit of output. In addition, trading countries may come under pressure to improve environmental standards when product quality or trans-boundary impacts are at issue, such as pesticide residues on food or water pollution in rivers that cross national boundaries.

We sometimes hear trade issues presented as a conflict between those who are "pro-trade" and those who are "anti-trade." But international trade is an established part of modern economic life. The important question for our purposes is how we can balance the economic gains from trade against the reality that trade shifts environmental impacts, sometimes increasing and sometimes decreasing total external costs? (There is a similar debate about social impacts of trade; we will not explore this in depth here, but the issues often overlap with those of environmental impacts). To help us answer this question we need delve further into the current policy context of trade issues.

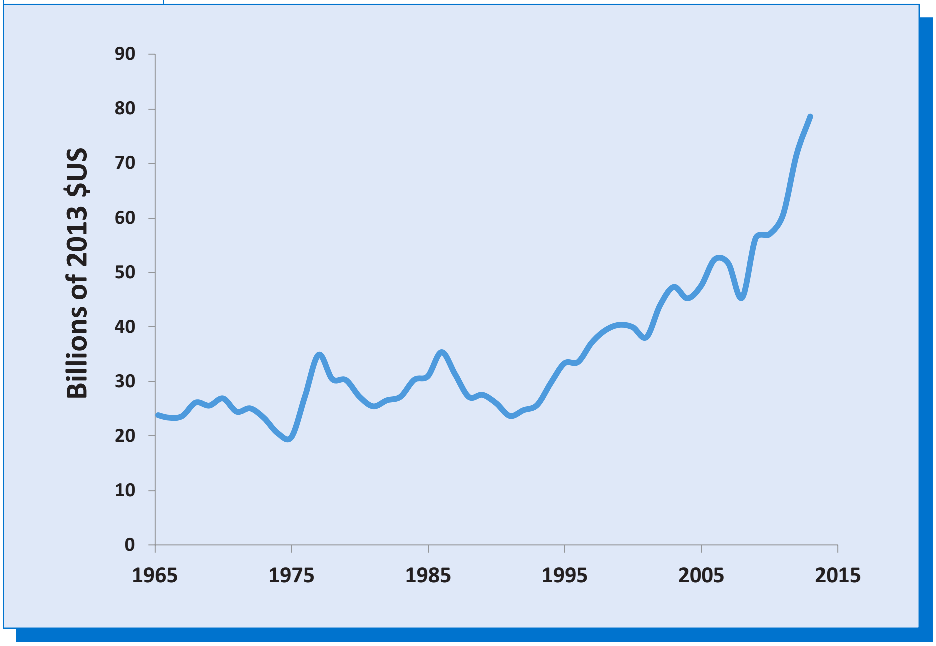
21.2 TRADE AND ENVIRONMENT: POLICY AND PRACTICE

Let us consider some practical examples of the environmental impacts of trade. Many developing countries grow agricultural crops for domestic sale as well as for export. As global trade has increased developing countries have devoted more land to growing export crops. We see in Figure 21.5 that agricultural exports, adjusted for inflation, among countries classified as low-income food-deficit[5] by the Food and Agriculture Organization were relatively stable up to the mid-1990s. These countries face widespread food insecurity, and are also vulnerable to food supply shocks, such as price changes or natural disasters, that can put vulnerable populations at high nutritional risk.[6] Despite these risks, we see that since the mid-1990s their food exports have increased significantly, especially in recent years. In many cases developing countries increase agricultural exports due to "structural adjustment" policies required by international agencies such as the International Monetary Fund (IMF) and the World Bank, which we'll discuss more in the next chapter. The goal of expanding exports is to bring more revenue to the country. But we also need to consider the social and environmental costs.

What are some of the environmental impacts of expanded agricultural exports? As we saw in Chapter 19, expansion of export agriculture can lead to deforestation as tropical forests are cleared to grow crops such as coffee, palm oil trees, and soybeans, as well as create pasture to raise livestock for meat exports. In addition to the loss of biodiversity and ecosystem services associated with deforestation, expansion of export crops often places greater demands on a country's water resources, as many export crops require intensive irrigation.[7]

Expansion of agricultural exports is also likely to increase a country's use of agricultural chemicals. A 2008 study found that a significant positive relationship between a

Figure 21.5 Real Agricultural Exports, Low-Income Food-Deficit Countries, 1965–2013



Source: Food and Agriculture Organization, FAOSTAT database.

Note: Nominal export values converted to real values based on the FAO's Food Price Index.

country's export-focused agricultural production and its use of fertilizers and pesticides. The paper concludes:

> [Traditional economic models] assume that free trade will allow market mechanisms to diminish environmentally degrading production practices and create a more resource efficient system of trade. Our results do not give compelling indications that this process is occurring in relation to trade in agricultural products and the use of fertilizer and pesticides. . . . Our results at least suggest that the claim of international organizations, such as the WTO, that increasing export agriculture will benefit the welfare of national populations and the environment, should receive further scrutiny.[8]

A similar study in 2011 analyzed the relationship between agricultural exports, pollution, and a country's overall health. Using data from over 100 countries, the paper found that increasing agricultural exports increases emissions of methane and nitrous oxide (both greenhouse gases) from the agricultural sector, and also reduces water quality. Further, increased agricultural pollution was associated with an increase in child mortality and a reduction in life expectancy.[9]

In some cases export crops can be more environmentally-friendly than the domestic crops that they replace. In Latin America and Africa, tree crops such as coffee and cocoa can help prevent erosion. In Kenya, the rapidly expanding horticulture export sector has had mixed environmental effects. Flower crops require high application rates of water and pesticides, and also displace land that could be used for local food production. But employment on flower farms can provide an alternative to environmentally-destructive exploitation of marginal lands for subsistence farming. The flowers are flown to Europe by jet, raising the issue of transportation energy use, but the energy consumed in jet fuel approximately equals the energy needed to grow similar flowers in heated greenhouses in Europe. Some Kenyan growers produce "fair-trade" flowers under a code that reduces water and pesticide use and guarantees workers higher wages, giving them a steady and reliable income.[10]

dualistic land ownership an ownership pattern, common in developing countries, in which large landowners wield considerable power and small landowners tend to be displaced or forced onto inferior land.

Social and environmental impacts often depend not on trade alone but on domestic political conditions. **Dualistic land ownership**, with large landowners wielding considerable political power and small farmers being displaced by export-oriented agriculture, can be doubly damaging to the environment. In Central America, for example, improved transportation and trade infrastructure led to "a technical shift to higher-profit, input-dependent farming. Maize and beans gave way to cotton, tomatoes, strawberries, and bananas. The value of farmland naturally increased, which benefited privileged landowning elites but led many poor farmers to be promptly evicted. These farmers had no choice but to move on to drier lands, forests, hillsides, or lands with shallow and less fertile soils." At the same time, the affluent farmers "use their influence to demand environmentally damaging input subsidies, which in turn lead them to over-mechanize, over-irrigate, and overspray."[11]

Health and safety issues that arise from trade are not always easily resolved at either the domestic or international level. For example, domestic regulations that prohibit the sale of toxic pesticides may not apply internationally. "Goods that are restricted in domestic markets, on the grounds that they present a danger to human, animal or plant life or health, or to the environment, may often be legally exported. This may cause a problem for the importing country, where information is lacking on whether and why the product is banned: exporters may make false declarations, customs authorities (particularly in developing countries) may lack adequate product testing facilities."[12]

WTO's Article XX a World Trade Organization rule allowing countries to restrict trade in order to conserve exhaustible natural resources or to protect human, animal, or plant life or health.

precautionary principle the view that policies should account for uncertainty by taking steps to avoid low-probability but catastrophic events.

According to the **WTO's Article XX**, countries may restrict trade in order to "conserve exhaustible natural resources" or to protect "human, animal or plant life or health." However, interpretation of this special exception to free trade rules has led to fiercely contested disputes among countries.

For example, starting in the 1990s, European countries refused to allow imports of U.S. and Canadian beef produced with hormone supplements. The United States and Canada argued that since there is no proven harm to human health from beef hormones, this ban constituted an illegal barrier to trade. The Europeans, however, cited the **precautionary principle**: Because their consumers are concerned about the possible effects of hormones, shouldn't they have the prerogative to decide what they will allow for domestic consumption? The long-standing trade dispute was eventually settled in 2012, with an agreement that allowed the European Union to maintain its ban on imports of hormone-treated beef, in return for increasing its quota for imports of high-quality beef from the United States and Canada.[13]

Product and Process Issues

A similar issue has arisen over the use of genetically engineered crops. Although unlabeled genetically engineered foods are allowed in the United States, they are widely opposed in Europe. Should European countries be able to ban the importation of genetically engineered foods? The issue has enormous implications both for agribusinesses that see great profit potential in genetic engineering and for many consumers who strongly oppose it.

The issue is further complicated because the opposition to genetic engineering is based in part not on human health effects (which, if proved, would be a valid reason for trade restrictions under Article XX) but on the likely environmental impacts of genetically engineered crops. Pollen from such crops can spread into the environment, disrupting fragile ecosystems, endangering neighboring organic farms, and possibly creating "superweeds" resistant to herbicides. But under GATT and WTO rules, the process by which a product is produced is not an acceptable cause for trade restrictions. Only if the product itself is harmful can a country impose controls.

For example, if pesticide residues at dangerous levels are detected on fruit or vegetables, imports of those products can be banned. But if the overuse of pesticides is causing environmental damage in the producing areas, the importing country has no right to act. Similarly, if rainforests are being destroyed by unrestricted logging, it is not permissible for countries to impose a ban on the importation of unsustainably produced timber.

The **process and production methods (PPM)** rule removes an important potential weapon for international environmental protection. If a country fails to act to protect its own environment, other countries have no trade leverage to promote better environmental practices. Only if a specific **multilateral environmental agreement (MEA),** such as the Convention on International Trade in Endangered Species (CITES), is in place are import restrictions permissible.

This principle was at issue in the tuna/dolphin decision, in which trade authorities ruled that countries had no jurisdiction over extraterritorial environmental issues. But such issues are more and more common in an increasingly globalized world. Simply waiting for the producing country to "clean up its act" is likely to be insufficient.

Globalization of trade can also create "boomerang" effects through the trans-boundary exchange of externalities. For example, pesticides banned in the United States are often exported to developing countries. Farm laborers who apply pesticides without safety precautions suffer harmful effects, as do adults and children who drink water from streams polluted by runoff. In addition, harmful effects return to the United States through trade in fruits containing residues of dangerous chemicals.

Trade can affect domestic as well as international policy, weakening the autonomy of countries to define their own environmental and social policies. Concerns have arisen of a **"race to the bottom,"** in which countries reduce environmental and social standards in order to gain competitive advantage.

> **process and production methods (PPMs)** international trade rules stating that an importing country cannot use trade barriers or penalties against another country for failure to meet environmental or social standards related to the process of production.
>
> **multilateral environmental agreements (MEAs)** international treaties between countries on environmental issues, such as the Convention on Trade in Endangered Species.
>
> **"race to the bottom"** the tendency for countries to weaken national environmental standards to attract foreign businesses or to keep existing businesses from moving to other countries.

> Producers located in member states enforcing strict process standards will suffer a competitive disadvantage compared with producers located in member states enforcing less strict standards. . . . [F]aced with the prospect of their industries suffering a competitive disadvantage when compared with companies located in low-standard jurisdictions, member states may choose not to elevate environmental standards or may even relax current standards.[14]

Based on a review of economic studies, a 2009 analysis concludes that there is little empirical evidence of a widespread "race to the bottom" among competing nations.[15] But even if countries don't specifically lower environmental standards to gain a competitive trade advantage, multinational companies may seek to produce their goods in countries with relatively lax environmental regulations in order to produce at lower cost. This can result in a **pollution haven** effect, where foreign investment and pollution shifts to countries with lower environmental standards. Most empirical tests of the pollution haven hypothesis dating from the 1990s and early 2000s found little evidence that international trade levels in a country were related to the stringency of environmental regulations.[16] But several recent studies using more sophisticated statistical techniques provide supporting evidence, at least in some instances. For example, a 2015 paper found that foreign investment by the United States was negatively related to the degree of regulation of carbon dioxide and sulfur dioxide in a country. Further, stricter environmental regulations in surrounding countries will cause more foreign investment to flow into a particular country, as its environmental regulations appear comparatively weak.[17]

pollution haven a country or region that attracts high-polluting industries due to low levels of environmental regulation.

A 2016 analysis by the OECD found no overall evidence of the pollution haven hypothesis when all manufacturing goods were aggregated, but did find that strict environmental regulations created a comparative disadvantage in "dirty" industries such as chemicals and fuel products. On the other hand, strict environmental regulations were likely to attract "clean" industries such as recycling.[18]

Another concern is that competitive pressures may exert a "chilling" effect on countries considering strict environmental laws. The North American Free Trade Agreement (NAFTA) has produced cases in which corporations have challenged environmental regulations as barriers to trade, using the Investor-State Dispute Settlement (ISDS) system included in the treaty. The Canadian asbestos industry sought to remove U.S. restrictions on the sale of cancer-causing asbestos products, and the U.S. pesticide industry challenged strong Canadian pesticide regulations. In one case, Ethyl Corporation (based in the United States) successfully overturned a Canadian ban on the importation and sale of the gasoline additive MMT, a chemical suspected of causing nerve damage. Canada was required not only to eliminate the ban but also to pay $13 million to compensate Ethyl Corporation for legal costs and lost sales.[19] Similar issues have arisen with ISDS provisions in the Dominican Republic-Central America Free Trade Agreement (DR-CAFTA). "In 2009, the U.S.-based Commerce Group sued El Salvador for closing a highly polluting mine. The case was dismissed in 2011for lack of jurisdiction, but El Salvador still had to pay several million dollars in fees for its defense. In a case still in process, the gold-mining conglomerate Pacific Rim has also sued El Salvador under DR-CAFTA for its anti-mining regulations."[20]

Environmentally Beneficial Effects of Trade

Trade expansion may also have direct or indirect beneficial effects on the environment. According to comparative advantage theory, trade causes countries to become more efficient in their use of resources, thereby conserving resources and avoiding waste. Trade liberalization may also remove **distortionary subsidies** and pricing policies, improving the efficiency of resource allocation. For example, widespread subsidies on chemical fertilizers and pesticides promote environmentally harmful farming methods, but trade agreements often prohibit such subsidies to domestic producers. Eliminating these subsidies would promote both economic efficiency and environmental sustainability.

distortionary subsidies subsidies that alter the market equilibrium in ways that are harmful to economic efficiency.

Trade may also encourage the spread of environmentally-friendly technology. In energy production, for example, many developing and formerly communist countries depend heavily on old, inefficient,

scale, composition, and technique effects the impacts of trade on economic growth, industrial patterns, and technological progress; the combination of effects may be environmentally negative, positive, or neutral.

highly polluting power plants. Trade can facilitate the replacement of these plants with modern, highly efficient facilities or (as in India) encourage a growing wind-power sector. Multinational companies, sometimes seen as offenders in the exploitation of developing country resources, can also introduce efficient technologies in industrial sectors. Multinationals may respond to domestic political pressures to develop cleaner industrial processes and then disseminate those processes throughout their worldwide operations.[21] Foreign investment in the manufacturing sector is particularly likely to result in the replacement of older technologies and equipment with newer production methods that are less resource- and pollution-intensive.[22]

One way of capturing trade's differential effects on the environment is to distinguish among **scale, composition, and technique effects**. Trade promotes growth (increased scale), changes in industrial patterns (composition), and improvements in technological efficiency (technique). "If the nature of [an economic] activity is unchanged but the scale is growing, then pollution and resource depletion will increase along with output."[23] Composition effects may shift a country's production in the direction of either more or less polluting industries. Technique effects can lead to a decline in pollution due to more efficient production and the use of cleaner technologies. The combination of the three effects may increase or decrease pollution levels or balance out to leave pollution levels unchanged. One study of sulfur dioxide pollution found that, on balance, trade reduces pollution levels[24]—but this may not be true for other pollutants.

Trade and Global Climate Change

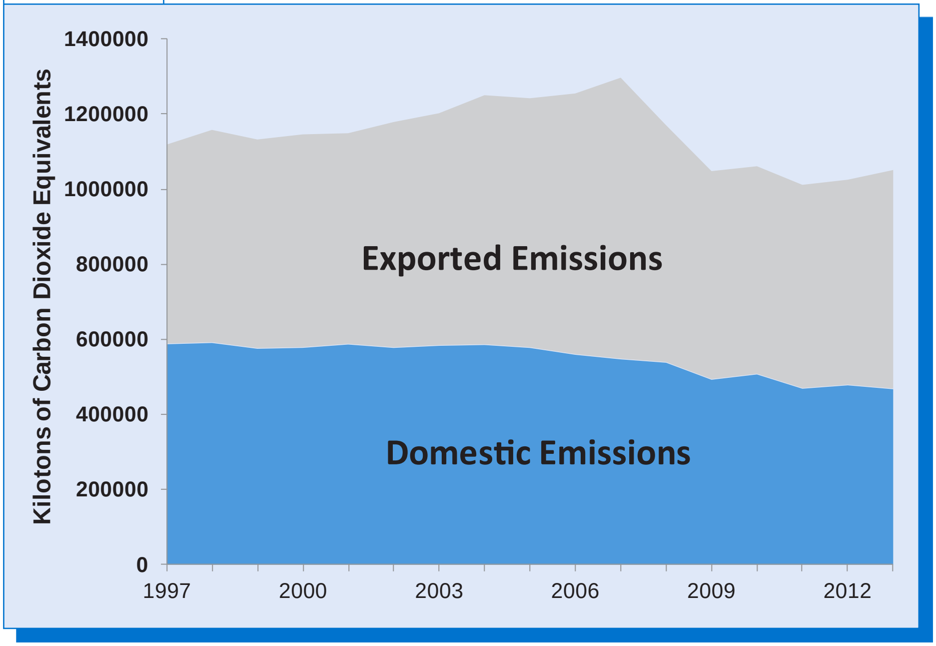
Trade has important effects on the emission of carbon dioxide and other gases that contribute to global climate change. As noted above, increased transportation resulting from expanded trade can result in higher transport-related emissions. Trade also shifts the patterns of carbon emissions, with a significant amount of "exported pollution"—carbon emissions associated with consumption of imported goods.

Recall our discussion of decoupling in Chapter 14. We specifically noted that the United Kingdom (Figure 14.5) appeared to have decoupled its CO_2 emissions from economic growth. While GDP in the UK grew by a factor of 2.6 between 1970 and 2013 its CO_2 emissions declined more than 30 percent. But we also mentioned that the reduction in CO_2 emissions failed to account for exported emissions. If we account for the emissions from goods produced in other countries but exported to the UK, does the country still show a reduction in total emissions?

decoupling breaking the correlation between increased economic activity and similar increases in environmental impacts.

Figure 21.6 presents domestic as well as exported greenhouse gas emissions associated with UK residential and industrial consumption from 1997 to 2013. One conclusion of this analysis is that a significant portion of the emissions associated with UK consumption is generated outside of the country. In 2013 exported emissions, generated outside of the UK, account for 55 percent of the total emissions generated by UK demand. This percentage is up from 47 percent in 1997, indicating that an increasing proportion of UK's emissions are exported. A second conclusion is that the UK's progress in reducing its greenhouse gas emissions is not as significant as official statistics indicate. Looking only at domestic emissions, Figure 21.6 shows that greenhouse gas emissions decreased by over 20 percent between 1997 and 2013. But if we add in exported emissions,

Figure 21.6 United Kingdom Domestic and Exported Emissions of Greenhouse Gases, 1997–2013



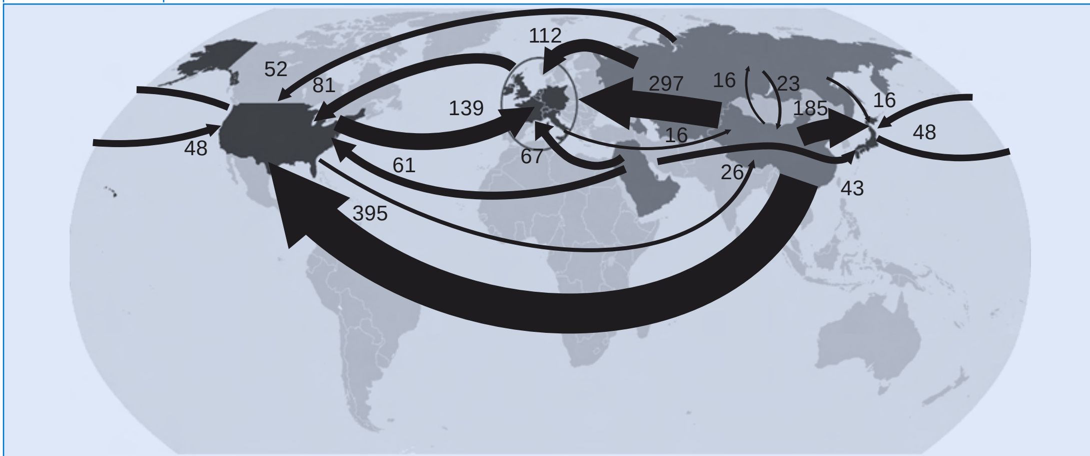
Source: UK Department for Environment, Food, and Rural Affairs, "UK's Carbon Footprint," https://www.gov.uk/government/statistics/uks-carbon-footprint.

the UK's total emissions have declined by only 6 percent.[25] Detailed estimates of where the UK's exported emissions are generated show that they originate all over the world, including other European countries, North America, China, and other Asian countries.[26]

The global magnitude of exported carbon emissions is shown in Figure 21.7. This shows major carbon flows in international trade, based on an analysis of the carbon content of internationally traded goods. Clearly, a significant portion of carbon emissions, especially from China, is associated with goods produced for export in the developing countries of the "global South" and consumed in the United States and Europe (the "global North"). According to an analysis by the OECD, China's carbon emissions would be about 13 percent lower if we only counted those emissions that resulted from domestic demand. Most developed nations are net exporters of carbon emissions, meaning their emissions would be higher if we allocated emissions based on a country's domestic demand, rather than its domestic production.[27]

This has important implications for international negotiations on global climate change. It would seem that those who consume the goods, not those who produce them, have the responsibility to reduce emissions.[28] The 2015 Paris Climate Agreement, however, adopted the traditional approach to measuring emissions, considering only where the emissions are generated. This adds strength to the "greenhouse development rights" argument, outlined in Chapter 13, that developed countries should contribute to the costs of reducing emissions in developing countries, since a significant portion of the emissions in developing countries are apparently a result of production of exported goods that are consumed in developed countries.

Figure 21.7 Carbon Flows in International Trade



Source: Davis and Caldeira, 2010.

Note: Figures are in million metric tons of CO_2 per year). Carbon flows to and from Western Europe are aggregated to include the United Kingdom, France, Germany, Switzerland, Italy, Spain, Luxembourg, the Netherlands, and Sweden.

21.3 TRADE AGREEMENTS AND THE ENVIRONMENT

A variety of institutional and policy approaches have been suggested to balance the goals of trade benefits and environmental protection, some similar to the standard free-trade model and others significantly different. We examine several of them.

The World Trade Organization Approach

This approach retains the overarching policy goal of free or "liberalized" trade, pursued for seven decades through "rounds" of trade agreements under the GATT, and its successor the WTO. The WTO, whose membership now comprises 164 countries, has worked to lower tariffs (taxes imposed on traded goods) and non-tariff barriers to trade as well as eliminate subsidies for export industries.

Although the WTO recognizes a special exception to trade rules under Article XX for resource conservation and environmental protection, its panel rulings have interpreted this fairly narrowly. WTO authorities tend to be suspicious of "green protectionism"—the use of trade barriers to protect domestic industry from competition under the guise of environmental regulation. They are also unsympathetic to countries' efforts to affect environmental policy outside their borders through trade measures.

The WTO has established a Committee on Trade and the Environment, which has addressed some environmental concerns but in rather general terms. According to the WTO website, the committee "has contributed to identifying and understanding the relationship between trade and the environment in order to promote sustainable development."[29] But critics contend that the Committee has produced only "weak policy outcomes," and will continue to do so until environmental concerns become fully integrated into the WTO's mission.[30]

From the WTO perspective, environmental policy responsibility should remain primarily at the national level. As far as possible, decisions on international trade policy should not be complicated with environmental issues. This is consistent with an economic principle known as the **specificity rule**: policy solutions should directly target the source of the problem. Using trade measures to accomplish environmental policy goals is therefore a **second-best solution** likely to cause other, undesired effects such as economic losses from trade restriction.

specificity rule the view that policy solutions should be targeted directly at the source of a problem.

second-best solution a policy solution to a problem that fails to maximize potential net social benefits, but that may be desirable if the optimal solution cannot be achieved.

This argument, which places the responsibility for environmental policies on national governments, has been criticized on several grounds. It fails to consider the competitive pressures that may encourage trading countries to reduce environmental protections, as well as the weak regulatory institutions in many developing countries. It is also inadequate for dealing with global environmental issues, such as climate change and biodiversity, that transcend national boundaries.

The NAFTA Approach

In 1993, the United States, Canada, and Mexico signed the North American Free Trade Agreement (NAFTA), lowering trade barriers across North America. During negotiations, environmental groups argued strongly that freer trade could have negative environmental consequences, pointing to the severe environmental problems already affecting the *maquiladoras*, which are industrial zones along the Mexican border in which materials and equipment can be imported duty-free for assembly and re-export. As a result, a **side agreement**, the North American Agreement on Environmental Cooperation (NAAEC), set up the tripartite Commission for Environmental Cooperation (CEC), and another side agreement, the North American Agreement on Labor Cooperation (NAALC), dealt with labor issues.

side agreement a provision related to a trade treaty dealing with social or environmental issues.

This specific attention to social and environmental aspects of trade was remarkable and almost unprecedented in trade agreements. Although this unusual aspect of NAFTA persuaded some environmental groups in the United States to support the agreement, the CEC has few enforcement powers. It may respond to a country's failure to enforce existing environmental regulations, but its role is generally limited to producing a fact-finding report and offering recommendations to the government involved.

The opening of agricultural sector trade under NAFTA has both social and environmental effects, as small corn farmers in Mexico are unable to compete with cheaper grain imported from the United States. The migration of displaced farmers from rural to urban areas has intensified urban environmental pressures as well as creating greater pressure for illegal migration across the U.S.-Mexican border. In addition, the genetic diversity characteristic of small-scale farming may be threatened, which could result in the loss of a "living seed bank" of great importance to world agriculture.[31]

In the area of industrial pollution, NAFTA has had both positive and negative impacts. Mexican environmental enforcement has improved, but increased industrial concentrations have led to worsened local environmental quality in some areas. A review of NAFTA's environmental provisions concluded that it has "fallen well short of the aspirations of the environmental community" and "should be strengthened in the next phase of NAFTA."[32] Further trade negotiations between the NAFTA countries and various Central American countries, however, have failed to reconcile the goals of environmental quality and trade benefits.

One of the most controversial aspects of NAFTA is its Chapter 11, which protects foreign investors. Under this provision, investors who claim damage to their business from environmental regulations can sue governments to recover damages, and several suits have been successful. In 1999, when California ordered a phase-out of the gasoline additive and groundwater contaminant MTBE, the Canadian manufacturer Methanex sued for $1 billion in compensation. After a long legal battle, the claim was finally rejected by a NAFTA tribunal in 2005.[33] The issue of investor rights agreements has since become a major issue in other international trade agreements. In trade agreements with the Dominican Republic, Central American countries, and Peru, the United States has agreed on language that protects "bona fide environmental regulations" from being the subject of expropriation suits by corporations.[34] But no consistent approach to incorporating the environment into trade agreements has been developed.

The European Union Approach

harmonization of environmental standards the standardization of environmental standards across countries, as in the European Union.

The European Union (EU) is unusual in being a free-trade area with its own legislative and administrative institutions. Unlike the North American CEC, the EU has the power to make environmental regulations binding on its member countries. This is known as **harmonization of environmental standards**. Note, however, that this policy solution involves more than free trade; it entails a supranational authority with the power to set environmental standards.

Regional trade area policies also raise the issue of "harmonizing up" versus "harmonizing down." Some countries may be forced to tighten their environmental policies to meet EU standards. But others may find their environmental standards weakened. The EU overturned a law requiring returnable bottles in Denmark as a barrier to trade, and Norway chose not to join the EU in part out of fear that it would be compelled to modify strict domestic environmental regulations.

It is relatively rare for trade agreements to include the kind of enforceable supranational environmental regulations that exist in the EU. Although the Standards Code adopted after the Uruguay Round of GATT trade negotiations in 1992 calls for international harmonization of environmental standards, no basis exists for this process to be other than voluntary.

Multilateral Environmental Agreements (MEAs)

It has long been recognized that some environmental problems require international solutions. The first international treaty dealing with trade and the environment was the Phylloxera agreement of 1878, restricting trade in grapevines to prevent the spread of pests that damage vineyards. In 1906 an international convention was adopted banning the use of phosphorus in matches. Phosphorous was responsible for serious occupational disease among match workers, but it was the cheapest ingredient for matches. An international convention was required to prevent any exporting country from gaining a competitive advantage by using phosphorus in match production.[35]

Since then, numerous international treaties have responded to specific environmental issues, such as conventions protecting fur seals, migratory birds, polar bears, whales, and endangered species. Transboundary and global environmental issues have been addressed in treaties such as the Montreal Protocol on Substances that Deplete the Ozone Layer (1987), the Basel Convention on Hazardous Wastes (1989), the Antarctica Treaty (1991), the Convention on Straddling and Highly Migratory Fish Stocks (1995), the Convention on Biological Diversity (2002), the Minamata Convention on Mercury (2013), and the Paris Climate Agreement (2015). These international treaties have addressed the environmental consequences of production methods in ways that individual countries cannot.

Serious questions remain, however, about the compatibility of MEAs with WTO rules. Which set of international agreements should take precedence in case of a conflict? For example, the Paris Climate Agreement encourages the transfer of energy-efficient technology to developing countries—but this provision could violate the WTO's prohibition of export subsidies. (For more on potential conflicts between the Paris Climate Agreement and trade deals, see Box 21.1.) Whereas national laws such as the U.S. Marine Mammal Protection Act have been found incompatible with WTO rules, so far no major test case has addressed conflict between an MEA and a trade agreement. But some analysts have argued that the possibility of a conflict with WTO rules has a "chilling" effect on the ability of MEAs to achieve their objectives.[36]

Box 21.1

THE PARIS CLIMATE AGREEMENT AND THE TRADE IN SERVICES AGREEMENT

Most of the public debates about trade focus on trade in goods, including agricultural products, fuels, manufactured products, and raw materials. But according to the WTO, over 20 percent of global trade is exports of commercial services, and this percentage has been increasing in recent years.[37] Major categories of services traded internationally include transportation, financial services, communication, and business services.

In 2012 negotiations started between 23 parties, including the European Union, Mexico, and the United States, to draft a treaty known as the Trade in Services Agreement (TISA). The negotiation process for TISA has been criticized for its high degree of secrecy, though a leaked draft of an "Energy Services Proposal" indicated that the TISA signatories would need to agree to "energy neutrality." This means that the member parties would not be allowed to create "market distortions" favoring renewable energy over fossil fuels.

The 2015 Paris Climate Agreement calls for policies that make "finance flows consistent with a pathway to low greenhouse gas emissions," implying the need for economic policies such as subsidies that would favor renewable energy. Susan Cohen Jehoram, a spokeswoman for Greenpeace, responded to the release of the "Energy Services Proposal" by noting that "If we want to reach [the Paris Climate target], governments will need a toolbox of measures that can give incentives to cleaner energy. TISA . . . would increase the power of multinationals to prevent governments taking desperately needed measures to decrease CO_2 levels."

Sources: Arthur Nelsen, "Global Trade Deal Threatens Paris Climate Goals, Leaked Documents Show." *The Guardian*, September 20, 2016; European Commission, "Trade in Services Agreement," http://ec.europa.eu/trade/policy/in-focus/tisa/.

21.4 STRATEGIES FOR SUSTAINABLE TRADE

The emerging twenty-first-century global economy will be characterized both by resource and environmental limits and by a much more important role for developing countries. Global trade has increased rapidly over the last several decades, from about 12 percent of global economic production in 1960 to 20 percent in 1990 and 29 percent in 2015.[38] Global trade volumes are expected to continue increasing in the future, although at a slower rate than in the past.[39]

Expanded global trade will bring benefits in terms of increased efficiency, technology transfer, and the importation and exportation of sustainably-produced products. But we must also evaluate the effects of trade in terms of social and ecological impacts, which can lead to conflicts between economic and environmental policy objectives.

> Much environmental damage is due to the increased scale of global economic activity. International trade constitutes a growing portion of that growing scale, making it increasingly important as a driver of environmental change. As economic globalization proceeds and the global nature of many environmental problems becomes more evident, there is bound to be friction between the multilateral systems of law and policy governing both.[40]

World Environmental Organization (WEO) a proposed international organization that would have oversight of global environmental issues.

The complexity of the international policy framework governing trade and environmental issues means that confusion often arises over which laws take precedence, or which organization has authority. These conflicts can be reduced if future trade agreements take environmental sustainability more explicitly into account. Introducing sustainability into trade policy will require institutional changes at global, regional, and local levels.

"Greening" Global Environmental Organizations

At the global level, advocates of institutional reform have proposed setting up a **World Environmental Organization (WEO)** that would counterbalance the WTO much as national environmental protection agencies balance departments of finance and commerce.[41] This would create a global environmental advocacy organization but might also lead to conflict and deadlock with other transnational institutions.

A WEO could also play a role in negotiating trade agreements on agricultural subsidies, seeking to redirect farm subsidies to soil conservation and development of low-input agricultural techniques. As global CO_2 emissions continue to rise, energy sector trade may need to accommodate a carbon tax or tradable permit scheme, as discussed in Chapter 13. Global agreements on forest and biodiversity preservation are also likely to involve specific trade restrictions, tariff preferences, or labeling systems. In all these areas, a powerful institutional advocate for environmental interests would have a major impact on the shaping of trade treaties and regulations.

Given that the creation of a WEO is currently unlikely, another approach would be to "green" existing institutions, broadening the environmental and social provisions of the WTO's Article XX, altering the missions of the World Bank and IMF to emphasize sustainable trade development objectives (discussed further in Chapter 22), establishing standard environmental protection provisions for bilateral and multilateral trade treaties.

Local, Regional, and Private Sector Policies

The trend toward globalization, which increasingly makes communities subject to the logic of the global marketplace, may come into conflict with the goal of strengthening local and regional policies promoting sustainable development. Reserving powers of resource conservation and management to local and national institutions is important to the sustainable management of resources. Most environmental protection policies are implemented at the national level, and it is important to maintain national authority to enforce environmental standards.

In regional groupings such as NAFTA that involve no supranational rule-making body, trade agreements could give special status to national policies aimed at sustainable agriculture and resource management. NAFTA rules currently give precedence to international environmental treaties (such as the Basel Convention on hazardous wastes, the Montreal Protocol on ozone-depleting substances, and CITES on endangered species). This principle could be expanded to all national environmental protection policies, and effective sanctions for environmental violations could be established.

Regional trade and customs unions such as the EU, with elected supranational policy-making bodies, can be responsible for environmental and social regulation to the extent that their legitimate democratic mandate allows. Trans-boundary issues are a logical area for supranational bodies to carry on environmental rule making. Where they are empowered to intervene in national policy-making, the process can be oriented toward "harmonizing up" rather than "harmonizing down" environmental standards. This means that countries within a free-trade area should retain the power to impose higher social and environmental standards where they see fit.

The development of certification and labeling requirements for sustainably produced products can arise from public or private initiative. Germany's "green dot" system for recyclable and recycled goods is one example. Private, nongovernmental organizations have also set up certification systems for goods such as coffee and timber. "Fair trade" networks certify socially and environmentally responsible production of traded goods. Although it represents only a tiny proportion of trade, the fair-trade industry has experienced a rapid rate of sales growth, exceeding $2.5 billion in worldwide sales by 2007.[42]

It is evident that there are many different approaches to reconciling the goals of trade and environment policy. An article reviewing the debate on trade and environment concludes that "there is no real choice about whether to address the trade and environment linkage; this linkage is a matter of fact. . . . Building environmental sensitivity into the trade regime in a thoughtful and systematic fashion should therefore be of interest to the trade community as well as environmental advocates."[43] Achieving this goal will be a major challenge for trade negotiators at both the regional and global level for the foreseeable future.

Summary

Trade expansion can often have environmental implications. Trade may increase environmental externalities at the national, regional, or global level. Although it is usually economically advantageous for countries to pursue their comparative advantage through trade, trade may have environmental repercussions such as increased pollution or natural resource degradation.

The environmental impacts of trade affect both importers and exporters. Agricultural cropping patterns altered by the introduction of export crops may involve environmental benefit or harm. Secondary effects of trade may arise from the disruption of existing communities, increased migration, and impact on marginal lands. Industrial pollution may increase, decrease, or shift regional impact.

International trade agreements make provisions for resource conservation and environmental protection, but these are usually limited exceptions to a general principle of free trade. In the World Trade Organization (WTO), countries may consider the environmental impact of a product but not of its production processes. This has led to numerous trade disputes over whether specific measures are justified on the grounds of protection of life and health or are simply disguised protectionism.

Policy responses to trade and environment issues can occur at the national, regional, or global level. The European Union is an example of a free-trade area that includes institutions for transnational environmental standards enforcement. The North American Free Trade Agreement was accompanied by a side agreement setting up an environmental monitoring authority, the Commission for Environmental Cooperation, but this body has little enforcement power.

Multilateral environmental agreements (MEAs) address specific trans-boundary or global environmental issues. Conflicts between MEAs and WTO rules are possible, but have so far largely been avoided. A major challenge for the future is dealing with the implications of carbon emissions reduction for international trade, including "exported emissions" by developed countries. Proposals have also been made for a World Environmental Organization to oversee global environmental policy and to advocate for environmental interests in the world trade system.

Where effective environmental protection policies are lacking at the regional or global level, national policies must address trade-related environmental issues. Certification and labeling requirements, instituted by governments or by private nongovernmental organizations, can help to promote consumer awareness and "greener" corporate practices in international trade.

Key Terms and Concepts

comparative advantage

consumption externalities

decoupling

distortionary subsidies

dualistic land ownership

exported emissions/pollution

gains from trade

General Agreement on Tariffs and Trade (GATT)

harmonization of environmental standards

multilateral environmental agreements (MEAs)

pollution havens

precautionary principle

process and production methods (PPMs)

production externalities

"race to the bottom"

scale, composition, and technique effects

second-best solution

side agreement

specificity rule

World Environmental Organization (WEO)

World Trade Organization (WTO)

WTO's Article XX

Discussion Questions

1. What are the welfare implications of trade in toxic wastes? Should such trade be banned or can it serve a useful function? Who should have the power to regulate trade in toxic wastes: individual countries, local communities, or a global authority?

2. Can harmonization of environmental standards solve the problem of environmental externalities in trade? How would the issues of harmonization differ in NAFTA, the EU, and the WTO? Would harmonization promote economic efficiency as well as environmental improvement, or might it lead to lower environmental standards?
3. What should be done if the provisions of a Multilateral Environmental Agreement conflict with the principles of the WTO? Which should take precedence, and who should have the authority to decide? Which economic, social, and ecological principles should be used to decide such issues? What specific issues regarding trade are associated with international climate agreements?

Notes

1. Trade in goods and services, based on 2015 data from the World Bank's World Development Indicators database.
2. This example shows trade in a relatively small country whose demand has no significant effect on world price, so world price is shown as constant (technically, an infinitely elastic supply curve at P_w). For a country large enough to affect world price, the world supply curve would be shown as upward sloping.
3. Similar to our analysis of an importing country, here we assume that the exporting country can sell all the timber they want at the prevailing world price.
4. See Gallagher, 2009.
5. Most low-income food-deficit countries are in Africa, as well as some in Asia and other regions. As of 2015 there were 54 such countries.
6. World Health Organization, http://apps.who.int/nutrition/landscape/help.aspx?menu=0&helpid=401.
7. Schaeffer, 2009.
8. Longo and York, 2008, p. 101.
9. Drabo, 2011.
10. See "Kenya's Flower Industry Shows Budding Improvement," *The Guardian*,, April 1, 2011, www.guardian.co.uk/environment/2011/apr/01/kenya-flower-industry-worker-conditions-water-tax/.
11. Paarlberg, 2000, p. 177.
12. Brack, 1998, p. 7.
13. See www.europarl.europa.eu/news/en/pressroom/content/20120314IPR40752/html/Win-win-ending-to-the-hormone-beef-trade-war/.
14. Brack, 1998, p. 113.
15. Frankel, 2009.
16. Kellogg, 2006.
17. Tang, 2015.
18. Koźluk and Timiliotis, 2016.
19. See www.cela.ca/article/international-trade-agreements-commentary/how-canada-became-shill-ethyl-corp/
20. Manuel Perez-Rocha and Julia Paley, "What 'Free Trade' has done to Central America," *Foreign Policy in Focus* November 21, 2014, http://fpif.org/free-trade-done-central-america/.
21. See Zarsky, 2004.
22. Neumayer, 2001.
23. Gallagher, 2009.
24. Antweiler *et al.*, 2001.

25. Data from the UK Department of Environment, Food, and Rural Affairs, "UK's Carbon Footprint," https://www.gov.uk/government/statistics/uks-carbon-footprint.
26. Carbon Brief, "Are the UK's Emissions Really Falling or Has it Outsourced them to China?" March 19, 2015, https://www.carbonbrief.org/are-the-uks-emissions-really-falling-or-has-it-outsourced-them-to-china
27. Wiebe and Yamano, 2016.
28. See Davis and Caldeira, 2010; Giljum and Eisenmenger, 2004.
29. https://www.wto.org/english/tratop_e/envir_e/wrk_committee_e.htm.
30. Gabler, 2010.
31. See Wise, 2007 and 2011.
32. Hufbauer *et al.*, 2000, p. 62. See also Deere and Esty, 2002; Gallagher, 2004.
33. See Mann, 2005.
34. Gallagher, 2009, p. 296.
35. Charnovitz 1996, pp. 176–177.
36. Gallagher, 2009.
37. WTO, 2015.
38. Data from World Bank, World Development Indicators database.
39. WTO, 2016.
40. UNEP and IISD, 2005, p. 2.
41. See Biermann and Bauer, 2005; http://www.unep.org/environmentalgovernance/PerspectivesonRIO20/ZakriAbdulHamid1/tabid/78591/Default.aspx.
42. See www.fairtradefederation.org for a review of fair trade initiatives.
43. Esty, 2001, pp. 114, 126–127.

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Web Sites

1. **www.wto.org/english/tratop_e/envir_e/envir_e.htm.** The World Trade Organization's web site devoted to the relationship between international trade issues and environmental quality. The site includes links to many research reports and other information.

2. **www.cec.org.** Homepage for the Commission on Environmental Cooperation, created under the North American Free Trade Agreement "to address regional environmental concerns, help prevent potential trade and environmental conflicts, and to promote the effective enforcement of environmental law." The site includes numerous publications on issues of trade and the environment in North America.

3. **www.oecd-ilibrary.org/environment/.** The web site for the environment division of the Organization for Economic Cooperation and Development, including many publications dealing with trade and environmental policy.

4. **www.iisd.org/library/environment-and-trade-handbook-second-edition.** This handbook, a joint effort of the International Institute for Sustainable Development and the United Nations Environment Programme, provides a guide to trade, environment, and development issues.

5. **www.fairtradefederation.org.** Homepage for the Fair Trade Federation, an organization dedicated to promoting socially and ecologically sustainable trade.

CHAPTER 22

Institutions and Policies for Sustainable Development

Chapter 22 Focus Questions

- Can the goals of economic development and environmental sustainability be reconciled?
- How can sustainability be pursued at global, regional, and local levels?
- What is the role of international development institutions in sustainable development?
- What are the central environment and development issues for the twenty-first century?

22.1 THE CONCEPT OF SUSTAINABLE DEVELOPMENT

In the past four decades, the role of the environment in economic development has moved from a neglected to a central issue in both developed and developing countries. This shift in perceptions, however, has not always translated into effective policies at the national and global level. One of the greatest impediments to designing and implementing policies to promote environmental sustainability has been the belief that such policies would hinder job creation and economic growth (an issue that was addressed in Chapter 14). This supposed contradiction found some resolution in the emergence of the concept of sustainable development in the late 1980s—a concept that has gained wide support in the past 30 years but also has been criticized as being too vague to lead to any significant change.

This chapter discusses the origins of the concept, the economic issues involved in sustainable development, and its strengths and limitations as a blueprint for new sets of policies. We explore how global institutions such as the United Nations have launched the Sustainable Development Goals as part of a global agenda for development, and how these goals are affecting the policies of international institutions.

We also focus on the limitations of these global institutions, and how, despite the new direction given by the UN Sustainable Development Goals and by the 2015 Paris Agreement on climate change, there are still contradictions between these objectives and some of the development policies promoted by international institutions. In the face of obstacles at the global level, we explore how local initiatives in urban and rural areas in both the Global North and Global South have been able to integrate the objectives of economic development and ecological sustainability and what lessons can be learned from such examples to address the challenges of the twenty-first century.[1]

22.2 THE ECONOMICS OF SUSTAINABLE DEVELOPMENT

All countries seek economic development. Economic development policies, however, have often paid limited attention to the environment. The need for specific action to protect the environment started to be recognized in the 1960s as people became aware of such issues as long-lasting ecological effects of pesticides, but the idea of modifying development paths to take account of environmental goals did not take hold until more recently.

The United States, for example, set up its Environmental Protection Agency in 1970. Prior to this a conservation movement, active for nearly a century, had focused primarily on protection of public lands. The idea that the industrial system should be subject to some sort of environmental controls was not an integral part of economic development theory or practice for most of the twentieth century.

By the end of the twentieth century, however, it had become clear that the issues of environment and development could not be separated. This gave rise to the concept of **sustainable development**. In 1987, the World Commission on Environment and Development (WCED) addressed the issue of conflicts between environment and development by proposing a definition:

> Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.[2]

sustainable development development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

According to the WCED (whose findings are also known as the Brundtland Report), the definition of sustainable development must reconcile two key concepts:

- The concept of "needs"—in particular the basic needs of the world's poor—which implies the issue of setting priorities dealing with ethical questions regarding the value of equity
- The idea of limits imposed by the environment's ability to meet both present and future needs, raising questions about balancing current and future needs

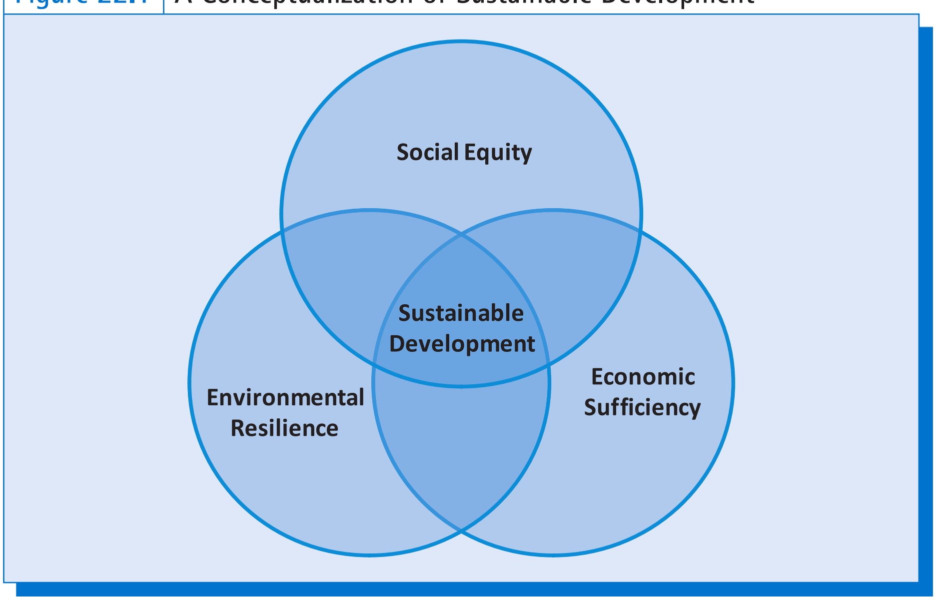
The concept of sustainable development originated by the WCED can also be conceptualized as having three dimensions: ecological, social, and economic, often represented in a diagram similar to Figure 22.1.

Full sustainability occurs at the intersection of these three dimensions—meeting the requirements of environmental resilience (the ability of natural ecosystems to renew and regenerate themselves), social equity (the necessity to meet human basic needs so that each individual can live a dignified life), and economic sufficiency (the requirement to provide sufficient economic production and employment). Each of these dimensions matters.

The concept of sustainable development can be interpreted in many ways. In a strictly economic fashion, it translates into the straightforward principle that an increase in well-being today should not result in reducing well-being tomorrow (i.e., that per-capita welfare should not be declining over time). But if wealth is created today by depleting the world's stock of natural capital, this cannot be considered as sustainable development.

At the intersection of economic necessities and environmental concerns and limits is the dimension of ecological sustainability. A major focus of this textbook has been to address the issues dealing with that intersection (for example, the consideration of planetary limits in Chapter 9 and of climate change in Chapters 12 and 13). But related social issues are no less critical to address:

Figure 22.1 A Conceptualization of Sustainable Development



- How societies deal with ecological limits and constraints raises the question of how social and cultural (including religious) norms can help or hinder the transition toward ecological sustainability. These norms can be transformed through education in order to make the transition to ecological sustainability socially, culturally, and politically acceptable.
- Social equity is also an essential part of the concept of sustainable development. An equitable society does not necessarily imply complete equality but, rather, economic justice and the provision of basic needs for all.

The concept of sustainable development has been widely accepted by various constituencies, including the business world, the political world, the scientific world, and the world of environmental activists and advocates. But precisely because of its all-encompassing nature, the term has been used and abused in many different ways, meaning different things to different people.[3] In this chapter, we attempt to identify the meaning of sustainability more specifically, both in theoretical and practical terms.

Sustainable Development: Implications for Developed and Developing Countries

The implications of making development socially and ecologically sustainable differ for developed and developing countries. Developed countries typically have large **capital stocks** and extensive infrastructure including power plants, highways, factories, extensive urban and suburban business and residential construction, dams, irrigation systems, and many other elements essential to modern economic production. This is both an advantage and disadvantage in trying to achieve environmental sustainability.

capital stock the existing quantity of capital in a given region, including manufactured, human, and natural capital.

On the one hand, greater economic capacity and advanced technology makes it more possible and affordable to put environmental protection systems in place. On the other hand, the large existing

Box 22.1
CHINA AND THE FUTURE OF THE GLOBAL ENVIRONMENT

A major factor affecting the future of the global environment is China's ability to develop economically without causing serious and irreversible ecological damage. With a population of close to 1.4 billion, China already uses about 22 percent of the world's commercial energy and is responsible for emitting about 29 percent of global carbon dioxide (CO_2) emissions. China has experienced the most rapid economic growth in the world, with an average of over 8 percent per year of real gross domestic product (GDP) growth from 2000 to 2013.

What will happen to the environment if China's growth continues? Even with relatively low per-capita impacts, the large total population in China (18.6 percent of global population as of 2016) means that China already causes significant global environmental impacts. China is already the world's largest energy consumer and largest emitter of CO_2.

As a result of rapid growth in industrial and agricultural production, China is facing an ecological and health crisis. In 2015, a scientific study analyzed four months' worth of hourly readings of air pollution taken at 1,500 ground stations in mainland China,

Table 22.1 Environmental Data for Selected Countries

Country		1. Energy Consumption[1]	2. CO_2 Emissions[2]		3. Motor Vehicles[3]
	2015 Population (millions)	2013 per capita	2013 per capita	2013 Total	2014 per 1,000 people
Bangladesh	161	216	0.4	69	3
China	1,371	2,226	7.6	10,249	83
France	66	3,840	5.1	333	578
India	1,311	606	1.6	2,035	18
Japan	127	3,570	9.8	1,243	591
Mexico	127	1,546	3.9	488	275
Thailand	68	1,988	4.5	303	206
United States	321	6,916	16.4	5,186	797
World	7,346	1,894	5.0	35,848	219

[1]Commercial energy from all sources, measured in kilograms of oil equivalent per capita, 2013 data.

[2]Emissions from industrial processes, measured in metric tons of CO_2 per capita, 2013 data. Totals in million metric tons.

[3]Includes automobiles, buses, and freight vehicles, 2014 data. Number of vehicles per thousand people.

Source for 1 and 2: World Bank, World Development Indicators database, http://data.worldbank.org/topic/.

Source for 3: Nation Master. 2014 data, http://www.nationmaster.com/country-info/stats/Transport/Road/Motor-vehicles-per-1000-people.

Taiwan, and other places in the region, including South Korea. Using a World Health Organization framework for projecting death rates from five diseases known to be associated with exposure to various levels of fine-particulate pollution, the researchers estimated the annual death toll caused by outdoor pollution to be (with 95 percent likelihood) between 700,000 and 2.2 million deaths, the midpoint of that range being 1.6 million a year, or about 4,400 people a day. In addition to air pollution, water pollution is also a cause of severe health and environmental problems. Around 90 percent of the sections of rivers around urban areas are heavily polluted.

In the past decade, China has started to take climate change seriously, by investing massively in wind and solar energy, becoming the world's largest manufacturer of wind turbines and solar panels and a leader in the development of carbon sequestration technology. In 2015, China has adopted an ambitious climate commitment, planning to reduce its carbon intensity (amount of carbon emitted per unit of GDP) by 60 to 65 percent by 2030, compared with 2005 levels, and to have its total CO_2 emissions peak by 2030. China's has also pledged to increase the share of non-fossil fuels in primary energy consumption to around 20 percent by 2030.

Sources: International Monetary Fund, 2012; Lee, 2011; U.S. Energy Information Administration, 2012; World Bank, 2007; Jim Yardley, "Rivers Run Black, and Chinese Die of Cancer," *New York Times*, September 12, 2004; Dan Levin, "Study Links Polluted Air in China to 1.6 Million Deaths a Year," *New York Times*, August 13, 2015.

Note: China real GDP growth rate data from: www.indexmundi.com/china/gdp_real_growth_rate.html, accessed October 2016.

technological and social lock-in dependence on a particular technology or accepted system of production and consumption.

stock of resource-using, waste- and pollution-generating capital, together with consumer demands for a continual flow of products, mean that developed countries may suffer **technological and social lock-in** to unsustainable methods of production. Technological lock-in includes, for example, a dependence on fossil fuels and the technologies associated with them. Social lock-in could include such factors as a reluctance to consider alternatives to automobile-based transport. In terms of the three-part graph presented in Figure 22.1, this creates a situation in which impediments to ecological sustainability may be both economic and sociocultural.

Developing countries have a different set of problems in achieving sustainability. Because they start from much lower income levels, their major social and economic goal is to increase production. As we have seen, many developing countries also tend to have considerable population growth momentum. The combination of increased population and economic growth creates strong pressure for rising resource use and increased generation of waste and pollution.

As shown in Table 22.1, developing countries, which for the most part still have a low environmental impact per capita, also have the demographic and economic potential to "catch up" to the high levels of environmental impact of most developed countries, if they follow similar patterns of development. Total CO_2 emissions in China, for example, are double those of the United States, although emissions per capita in China are half those of the U.S. India's per-capita energy consumption and CO_2 emissions are less than one-tenth of U.S. levels. If China and India both consumed energy at U.S. per capita levels, total world energy consumption would nearly double. If the whole world's population emitted CO_2 at the U.S. per capita level, global CO_2 emissions would more than triple.

Developing countries, however, may have greater choice as to which development path to pursue. They are not necessarily committed to following a resource-intensive, high waste-generating pattern of economic growth. As later participants in development, they may have access to improved technologies, especially with the assistance of developed countries, and can avoid costly environmental errors made by the developed countries (a phenomenon sometimes called "late-comers" advantage). But they will also find themselves competing with developed countries for limited resources and a limited environmental absorption capacity for global pollutants such as CO_2 (see Box 22.1).

22.3 REFORMING GLOBAL INSTITUTIONS

International institutions often have conflicting agendas, mirroring the tensions between the demand for economic growth and the need for human development and environmental protection. Both the World Bank and the IMF were founded in 1944 to stabilize the world financial system and promote economic development. The IMF "is charged with overseeing the international monetary system to ensure exchange rate stability and encouraging members to eliminate exchange restrictions that hinder trade," while the World Bank is "not a bank in the ordinary sense but a unique partnership to reduce poverty and support development," through providing loans, sometimes at reduced interest rates, to developing nations to "support a wide array of investments in such areas as education, health, public administration, infrastructure, financial and private sector development, agriculture, and environmental and natural resource management."[4] A third major international institution, the World Trade

Organization, was created in 1995 to replace the General Agreement on Tariffs and Trade (GATT), to regulate international trade between nations, focusing on lowering barriers to trade as a way to promote economic development. The World Bank, the IMF, and the WTO have as their overarching goal the promotion of economic development, which often comes at an environmental cost.

As we saw in Chapter 21, environmental issues remain controversial at the WTO. The IMF does not include environmental factors in its mandate, but its monetary policies have significant implications both for the environment and for relations between developed and developing countries. The World Bank has attempted to "green" its operations by giving environmental considerations a more prominent role in its policy making, but these efforts remain controversial, with critics arguing that development goals typically take priority.

In the 1980s and 1990s the World Bank was frequently a target of protest for funding environmentally destructive projects such as large dams and forest clearance. A study conducted in the 1990s by the World Wildlife Fund (WWF) concluded that **structural adjustment**[5] policies supported by the World Bank had led to increased consumption of renewable and nonrenewable resources, greater pressure on **environmental sink functions** of pollution absorption, a drawdown of **natural capital**, and a weakening of environmental institutional capacity.[6] In response to such criticisms, the World Bank has attempted to integrate the goals of environmental protection and sustainable development into its governance and decision-making process. As presented in a 2016 assessment of the World Bank by the Independent Evaluation Group (IEG):

> Environmental policy lending represents an important part of the Bank's work. Environmental policy lending began with a small number of operations in the 1990s, but commitments grew rapidly in the 2000s to a peak . . . of nearly $3 billion in 2009 and 2010. Though commitments declined after the [financial] crisis, the numbers of environmental Development Policy Operations (DPOs) have remained high by historical standards. [Environmental lending] has totaled over $14 billion since 2000.[7]

According to World Bank reports, "Average annual development policy lending (DPL) for environmental issues increased from US$438 million in FY04–08 to US$1.48 billion in FY09–13." Figure 22.2 shows the total value of World Bank environmental lending projects from 2000 to 2016. Considering all environmental and natural resource management projects, the total is higher: "the World Bank has committed $33 billion in funding for the environment and natural resource management over the past decade." This amount represents about 10 percent of total bank lending during this period.[8]

These projects include both a "brown agenda" (pollution management) and a "green agenda" (natural resource conservation) including forest management, integrated pest management, watershed rehabilitation, energy efficiency and renewables, and water management and sewer systems, sometimes in collaboration with other international environmental and development organizations.

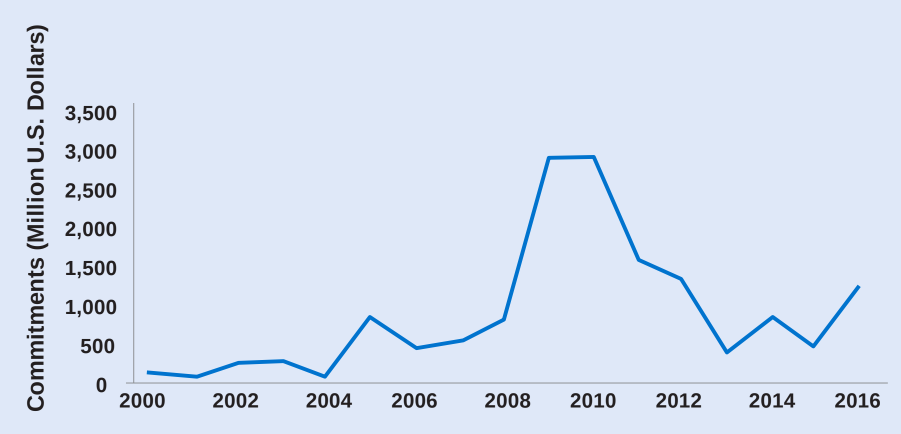
Rural development projects increasingly emphasize land resource management, soil and water conservation, and training in sustainable farming techniques. Urban development

structural adjustment policies to promote market-oriented economic reform in developing countries by making loans conditional on reforms such as controlling inflation, reducing trade barriers, and privatization of businesses.

environmental sink functions see "sink function."

natural capital the available endowment of land and resources, including air, water, soil, forests, fisheries, minerals, and ecological life-support systems.

Figure 22.2 World Bank Environmental Financing, Fiscal Years 2000–2016



Source: Independent Evaluation Group, 2016.

projects include water and sanitation upgrading and solid waste management. Energy lending includes promotion of energy efficiency and renewable energy sources, as well as development of cleaner fossil fuels such as natural gas. Examples of the World Bank's investment in projects with a dual goal—eradication of poverty and environmental sustainability—include large-scale efforts in rural solar electrification in Bangladesh (see Box 22.2).

As part of its "greening" efforts, the World Bank has also established a Carbon Finance Unit (CFU), which does not lend or grant resources to projects but, rather, contracts to purchase emission reductions, using money contributed by governments and companies in Organization for Economic Cooperation and Development (OECD) member countries, under carbon trading schemes such as those discussed in Chapter 13.[9] The World Bank's CFU is helping developing countries establish programs of reforestation that, at a larger scale, could mitigate some of the effects of climate change. Several of the poorest African countries, including Ethiopia and the Democratic Republic of Congo (DCR), receive funds for such projects (see Box 22.3).

Despite significant improvement in the environmental content of World Bank policies, critics have argued that there is still too much emphasis on traditional development projects without environmental considerations. A report from the World Resources Institute showed that between 2005 and 2007, less than 30 percent of the World Bank's lending to the energy sector had integrated climate considerations into project decision making, and that more than 50 percent of the World Bank's $1.8 billion energy-sector portfolio did not include climate change considerations.[10]

Because the World Bank provides loans, not grants, the funds must eventually be repaid. To promote debt repayment, the lenders emphasize export promotion, which can lead countries to liquidate natural assets, undermining their long-term economic prospects. In addition, large bureaucratic institutions dealing in billions of dollars often are poorly prepared to connect to sustainable initiatives at the local level.

The establishment of the Global Environmental Facility (GEF) is an attempt to develop a joint effort among several international institutions to promote sustainable development. Established in 1991 as a joint operation between ten international organizations, the GEF provides grants to developing countries and countries with economies in transition for projects related to biodiversity, climate change, international waters,

Box 22.2
RURAL ELECTRIFICATION AND RENEWABLE ENERGY DEVELOPMENT IN BANGLADESH

About half of Bangladesh's 150 million people lack access to reliable electricity. A large-scale rural electrification and renewable energy development project was launched in 2009, for which the World Bank approved a $130 million zero-interest International Development Association (IDA) loan and another $172 million loan in 2011. In two years, more than 1.4 million low-income rural households have gained access to electricity, delivered by solar photovoltaic (PV) panels, most of which are imported from China.

In addition to delivering power to unserved communities, it is helping to reduce carbon emissions from avoided use of kerosene and diesel for lighting.

The solar electrification industry and its supply chain in Bangladesh have also helped create, directly and indirectly, a total of about 50,000 jobs.

According to Vijay Iyer, the director of the Sustainable Energy Department at the World Bank:

> The drop in price of solar PV panels, combined with high prices for fossil fuels, slow pace of grid connections, along with the scale of cell-phone penetration among the poor, which is driving demand, has created vast new potential for off-grid solar—not just in Bangladesh, but in many other low-income countries.

According to a recent research report, the application of PV technology for rural electrification is indirectly increasing the income as well as the living standard of the rural poor in Bangladesh. Solar home systems installation has experienced explosive growth and created a $200 million PV market. The researchers conclude that "the case of Bangladesh could be replicated and launched in other parts of Asia to bolster the PV market."

Source: World Bank, "Energy from Solar Panels Transforms Lives in Rural Bangladesh," http://go.worldbank.org/SJPS5X0RG0/; Sharif and Mithila, 2013.

land degradation, the ozone layer, and chemicals. These projects benefit the global environment, linking local, national, and global environmental challenges and promoting sustainable livelihoods.

In the past 25 years, the GEF has allocated over $16 billion, supplemented by more than $90 billion in co-financing, for more than 4,000 projects in 166 developing countries and countries with economies in transition.[11]

Global Sustainable Development Goals

Between the first United Nations Conference on the Human Environment, held in Stockholm in 1972, and the Rio+20 Summit in 2012, an ambitious agenda emerged to push the international community of nation-states in the direction of greater commitments to human needs and environmental sustainability. Although it has often been difficult to reach any international consensus on specific targets, the United Nations member states agreed in 2000 to a statement of objectives known as the Millennium Development Goals, with a target date of 2015. In 2015 these were replaced and extended by the Sustainable Development Goals. While the focus in the first set of goals was primarily on human needs, the second round has a more detailed environmental emphasis.

Box 22.3
REFORESTATION IN ETHIOPIA AND THE DEMOCRATIC REPUBLIC OF CONGO

Ethiopia has lost 97 percent of its original forest, with dramatic consequences for both the livelihoods of local communities and biodiversity. The Humbo Ethiopia Assisted Natural Regeneration project (supported by the World Bank's Carbon Finance Unit) is restoring 2,700 hectares of a biodiverse native forest, while supporting local income and employment generation.

The Congo's rainforests are the second largest in the world after the Amazon, locking nearly 8 percent of the planet's carbon and having some of its richest biodiversity. Nearly 40 million people depend on the forests for medicines, shelter, timber, and food. After having been criticized for supporting "development" schemes encouraging destructive logging of the Congo's forests by foreign companies, the World Bank shifted to promotion of reforestation efforts.

On the Batéké plateau in the Democratic Republic of Congo, the ecosystem is composed of dry forest, and the lands are subject to uncontrolled degradation and deforestation due to charcoal production and subsistence agriculture. The Ibi Batéké Degraded Savannah Afforestation Project, financed by the World Bank, is converting 4,200 hectares of natural grassy savannah into an abundant and sustainable fuelwood supply for charcoal production. The project is encouraging the local population and farmers to stop the destruction of the natural forests and to concentrate on planting managed forests.

Sources: World Bank Carbon Finance Unit, http://wbcarbonfinance.org; John Vidal, "World Bank Accused of Razing Congo Forests," *The Guardian*, October 4, 2007.

A review of the eight Millennium Development Goals at the end of their target period indicates some successes, but partial and uneven accomplishment:[12]

1. Eradicate extreme poverty and hunger: Halve the proportion of people living on less than \$1.25 a day; halve the proportion of people who suffer from hunger—*Result*: The number of people living on less than \$1.25 a day has been reduced from 1.9 billion in 1990 to 836 million in 2015; the target of halving the proportion of people suffering from hunger was narrowly missed.
2. Achieve universal primary education: by 2015, all children can complete a full course of primary schooling, girls and boys—*Result*: the net enrollment rate increased from 83 percent in 2000 to 91 percent in 2015.
3. Promote gender equality and empower women: Eliminate gender disparity in education—*Result*: About two-thirds of developing countries have achieved gender parity in primary education.
4. Reduce child mortality: Reduce the under-five mortality rate by two-thirds—*Result*: The child mortality rate fell from 90 to 43 deaths per 1,000 live births.
5. Improve maternal health: Reduce maternal mortality ratio by three-quarters—*Result*: The global maternal mortality ratio has fallen by nearly half.
6. Combat HIV/AIDS, malaria, and other diseases: Halt and reverse the spread of HIV/AIDS, malaria, and other major diseases—*Result*: The number of new HIV infections fell by around 40 percent between 2000 and 2013, but the overall target was not met.

7. Ensure environmental sustainability: Integrate the principles of sustainable development into country policies and programs; reverse loss of environmental resources; reduce biodiversity loss, halve the proportion of the population without sustainable access to safe drinking water and basic sanitation—*Result*: the target of halving the proportion of people without access to water was achieved by 2010, but the sanitation goal was not.
8. Develop a global partnership for development: *Result*: Between 2000 and 2014, overseas development assistance from rich nations to developing countries increased by 66 percent in real terms, reaching $134.8 billion by 2013.

Progress on the MDGs has been uneven across countries. An estimated 15.5 percent of the world population still suffers from hunger, and many countries, particularly on the African continent, have not met the targeted two-thirds reduction in child mortality by 2015. In Sub-Saharan regions and Southern Asia, where 80 percent of people in extreme poverty live, progress in reaching MDGs has generally been very limited.[13]

The Sustainable Development Goals aim to continue and expand the MDG efforts.[14] They include more specific environmental goals including:

- Ensure sustainable consumption and production patterns
- Take urgent action to combat climate change and its impacts
- Conserve and sustainably use the oceans, seas, and marine resources for sustainable development
- Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation, and halt biodiversity loss

A major concern with achieving these goals is the financing needed. As noted in Chapter 13, the financial requirements for responding to climate change alone were at least $100 billion in aid to developing countries. A 2011 report found that the MDGs already suffered from a $120 billion expenditure shortfall.[15] The World Investment Report 2014, found that between $3.3 trillion and $4.5 trillion would be needed in the developing world to deliver the goals, and that the SDGs will fail unless governments and businesses find an extra $2.5 trillion a year to support them.[16]

As noted above, current environmental commitments by the World Bank and GEF are in the order of $1–3 billion per year, much less than the amounts being cited as needed for the SDGs. These amounts are also well in excess of the $100 billion pledged by developed nations as part of the 2015 Paris Agreement on climate change (see Chapter 13). A much larger combination of international, national, and private financing will clearly be required.

A related problem is the lack of strong international environmental governance. Over the past several decades a number of attempts have been made to propose the establishment of a United Nations Environment Organization. Such an organization could "be equipped with majority decision making as well as enforcement powers vis-à-vis states that fail to comply with international agreements on the protection of global commons."[17] Forty-six countries have affirmed their support for the creation of a United Nations Environment Organization, but major powers such as the United States, Russia, and China have declined to support such an initiative.[18]

Action at the Local Level: Sustainability from the Ground Up

As we have seen, the international record on moving toward sustainable development is very uneven. But great diversity and creativity have emerged at the local level, in cities, and in rural areas, in the North as well as in the South.

extractive reserves a forested area that is managed for sustainable harvests of non-timber products such as nuts, sap, and extracts.

agroforestry growing both tree and food crops on the same piece of land.

In the past 20 years, thousands of local initiatives have sprouted that respond to the necessities of ecological sustainability while improving people's livelihoods, through innovative initiatives in agriculture, forestry, resource management, biodiversity conservation, energy production, industrial recycling, and other areas.[19] Examples of such programs include:

- Organic farming cooperatives in the Philippines.
- **Extractive reserves** in the Brazilian rainforest promoting multiple-product forest management and conservation.
- Sustainable forestry and reforestation in the Peruvian Amazon and Costa Rica.
- Rural solar power installation in the Dominican Republic.
- Soil restoration and conservation technologies in Honduras.
- Women's cooperatives for farming, food processing, and light industry in Nigeria.
- **Agroforestry** programs in Guatemala, Haiti, and Indonesia.
- Solar cooker project in Senegal.
- Conservation of native potatoes, tubers, grains, and beans in Bolivia.
- Community seed banks to protect local indigenous varieties of grains (wheat, barley, corn, etc.) in Asia, Africa, and Latin America.
- Forest regeneration projects in Congo and in Ethiopia (see Box 22.3).
- Agroecology and soil regeneration projects in countries throughout Africa, Asia, and Latin America.[20]
- Reforestation in India, Kenya, and Haiti, and Morocco.[21]
- Coastal afforestation in Bangladesh.[22]

These examples of local sustainable development in practice demonstrate that the goals of economic development, poverty reduction, and environmental improvement can be successfully combined. Unfortunately, the principles embodied in these small-scale projects are rarely reflected in national and global economic priorities. This indicates the continuing need for a major reorientation of economic development policies.

Sustainability issues are increasingly important for urban areas. More than half the world's population lives in urban areas today, and by 2050 this proportion will be closer to 80 percent. Cities account for 50 percent of all waste, generate 60–80 percent of all greenhouse gas emissions, and consume 75 percent of natural resources, while occupying only 3 percent of the earth's land area.[23] At the Rio+20 Summit in 2012, a Global Town Hall was set up in which mayors from hundreds of cities exchanged ideas on urban sustainability practices including transportation, housing, waste disposal and recycling, energy efficiency, and water management.[24] (See Box 22.4.) An increasing number of cities have adopted sustainability agendas. International networks of cities include the C40 Cities Climate Leadership Group, the Compact of Mayors, the ICLEI-Local Governments for Sustainability, and the UCLG—United Cities and Local Governments.[25]

Box 22.4
SUSTAINABLE URBAN MANAGEMENT IN CURITIBA, BRAZIL

The city of Curitiba, Brazil, has been a pioneer in investing in sustainability, public transportation systems, and reduced carbon emissions, starting in the 1980s. Heralded as an example for other cities in the developing and the developed world, Curitiba is nonetheless facing several challenges in keeping its promise of sustainability in the face of rapid demographic growth.

A key component of Curitiba's success is the attention given to transportation issues. Zoning laws foster high-density development along transportation corridors served by buses. The bus system transports more than a million passengers per day. Gasoline use per capita and air pollution levels in Curitiba are among the lowest in Brazil. Although 60 percent of people own cars in Curitiba, busing, biking, and walking dominate, accounting for 80 percent of all trips in the city. The city emits 25 percent less carbon per capita than most Brazilian cities.

Curitiba has 52 square meters of green space per capita. The city's parks serve an ecological function, as well as being a public amenity. Much of the 400 square kilometers of parkland doubles as a natural, decentralized storm-water management facility.

Curitiba could not afford a large-scale recycling plant, but public education programs have been successful in reducing wastes and increasing recycling rates. In areas where streets are too narrow for garbage trucks to enter, incentives for community garbage collection have been created by exchanging filled garbage bags for bus tokens, parcels of surplus food, and school notebooks. In another program, older public buses are converted to mobile schools and travel to low-income neighborhoods.

The example of Curitiba shows that progress toward environmental sustainability is possible even in an urban area with increasing population and high poverty rates. These successes have not been without significant problems, however. Curitiba has grown in population from 300,000 in 1950 to around 3 million (including its greater metropolitan area). The city has had difficulty keeping up with demographic growth, and its landfill regularly overflows. Its development has contributed to dramatic deforestation: 99 percent in the state of Parana, of which Curitiba is the largest city. So, despite the success of aggressive urban planning measures undertaken starting 40 years ago, Curitiba must continue to update its initiatives and adapt to the times.

Sources: David Adler, "Story of Cities #37: How Radical Ideas Turned Curitiba into Brazil's 'Green Capital'," *The Guardian*, May 6, 2016; Brian Barth, "Curitiba: the Greenest City on Earth," *The Ecologist*, March 15, 2014; Green Planet Monitor, 2012.

22.4 NEW GOALS AND NEW PRODUCTION METHODS

Promoting ecological sustainability implies a major shift from existing techniques and organization of production. Examining the implications in terms of specific sectors of economic activity and drawing on the discussion in earlier chapters, we can summarize some of the needed changes.

Agriculture

Feeding an expanding population at higher per capita levels of consumption will impose a significant strain on global soil and water systems. The response to this must be twofold.

On the production side, current high-input techniques associated with soil degradation and water pollution and overdraft must give way to agroecological systems of organic soil rebuilding, integrated pest management, and efficient irrigation. This, in turn, implies much greater reliance on local knowledge and participatory input into the development of farming systems.[26]

On the consumption side, probable resource limitations on production will necessitate both population growth limits and greater food distribution equity and efficiency. As discussed in Chapter 15, effective policies can simultaneously promote social equity and moderate population growth, including women's education and health care and family planning services. Distribution and dietary patterns will need to emphasize affordable basic food stuff and vegetable-based proteins and nutrients.

Industry

As the scale of global industrial production grows, the inadequacy of "end-of-pipe" pollution control will be increasingly apparent. As we saw in Chapter 14, the concept of **industrial ecology** implies the restructuring of entire industrial sectors based on a goal of reducing emissions and reusing materials at all stages of the production cycle. A broad cooperative effort between corporations and governments is essential to achieve this goal.

industrial ecology the application of ecological principles to the management of industrial activity.

Energy

Both supply limits and environmental impacts, in particular the accumulation of greenhouse gases, mean that it will be necessary to accomplish a transition away from fossil fuels well before 2050, as discussed in Chapters 11, 12, and 13. A restructured energy system would be significantly less centralized, adapted to local conditions, based increasingly on high energy efficiency, and utilizing solar, wind, and sustainable biomass power sources. This will require a major mobilization of capital resources for the development of renewable energy sources in countries now rapidly expanding their energy systems.

Renewable Resource Systems

As discussed in Chapters 18, 19, and 20, world fisheries, forests, and water systems are severely overstressed. With even greater demands on all systems expected in coming decades, all levels of institutional management must be urgently reformed. Multilateral agreements and global funding are needed to conserve trans-boundary resources; natural resource management systems must be shifted from goals of exploitation to conservation and sustainable harvesting; and local communities must be strongly involved in resource conservation.

Water Resources

As discussed in Chapter 20, water scarcity, accentuated by climate change, will become a critical factor in many parts of the world during the twenty-first century. Increasing water efficiency and recycling (especially in agriculture), reducing water pollution, and extending water and sanitation access to low-income communities are essential for long-term sustainability.

Toward a Redefinition of Development

The goals of sustainable development policies can be viewed in terms of strong and weak sustainability, as discussed in Chapter 9. In general, advocates of **strong sustainability** argue that natural systems should be maintained intact wherever possible. They identify **critical natural capital**—such as water supplies—as resources to preserve under all circumstances. In this view, for example, maintaining soil's natural fertility is essential, even if it is possible to compensate for degraded soils with extra fertilizer. Under the more moderate approach of **weak sustainability**, some degradation or loss of natural capital is acceptable if it is compensated for by accumulation of **manufactured capital**.

Either concept of sustainability—but especially the strong version—implies changes in the standard conception of economic growth. Economic activity that relies heavily on natural resources, raw materials, and fossil fuels cannot grow indefinitely. Because the planetary ecosystem has certain limits, limits must also apply on a **macroeconomic scale**—the overall level of resource use and goods output, as discussed in Chapter 9. This implies a long-term need to reach a plateau in economic growth, eventually achieving a **steady state** economy in terms of the consumption of material and energy resources.[27]

This concept differs radically from the standard view of economic growth, in which GDP increases indefinitely on an **exponential growth** path—for example, GDP growth of 4 percent per year. In the limits-to-growth perspective, national and global economic systems must follow what is called a **logistic growth** pattern in which economic activity approaches a maximum, at least in terms of resource consumption (Figure 22.3).

This analysis implies constraints on material consumption, but activities that involve little or no resource consumption, or that are environmentally neutral or environmentally friendly, could grow indefinitely. Such activities could include services, arts, communication, and education. After basic needs are met and moderate levels of consumption are achieved, economic development could be increasingly oriented toward these kinds of inherently "sustainable" activities.[28]

Currently much of development theory and policy promote continuous economic growth. What kind of policies would promote sustainability? Are the goals of economic growth and sustainability compatible?

Some ecological economists view "sustainable growth" as a contradiction in terms. They point out that no system can grow without limit. However, certain kinds of economic growth are essential. The large number of people in the world who cannot satisfy basic needs require more and better food, housing, and other goods.

In high-consumption societies, improved well-being might be achieved through expanded educational and cultural services that, as we have noted, have little negative environmental impact. People might also choose more leisure time rather than

strong sustainability the view that natural and human-made capital are generally not substitutable and, therefore, natural capital levels should be maintained.

critical natural capital elements of natural capital for which there are no good human-made substitutes, such as basic water supplies and breathable air.

weak sustainability the view that natural capital depletion is justified as long as it is compensated for with increases in human-made capital; assumes that human-made capital can substitute for most types of natural capital.

manufactured capital productive resources produced by humans, such as factories, roads, and computers, also referred to as produced capital or human-made capital.

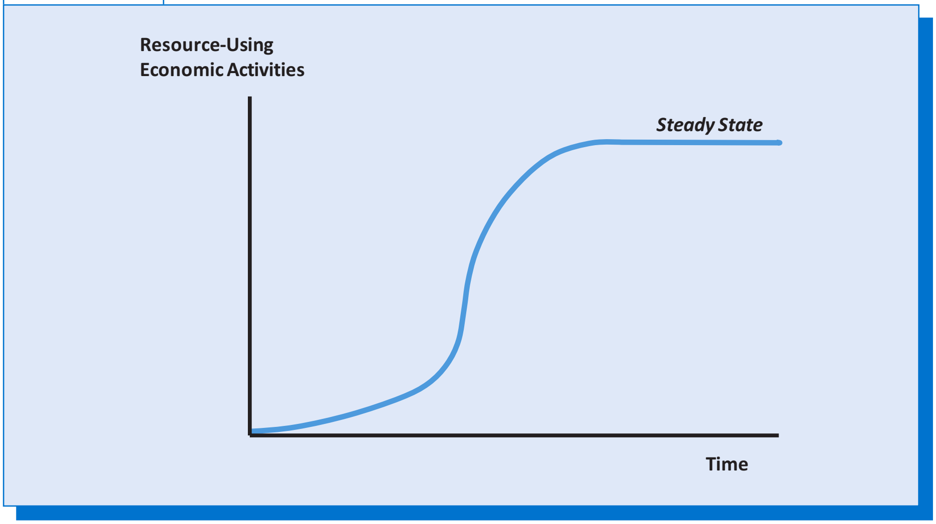
macroeconomic scale the total scale of an economy; ecological economics suggests that the ecosystem imposes scale limits on the macroeconomy.

steady state an economy that maintains a constant level of natural capital by limiting the throughput of material and energy resources.

exponential growth a value that increases by the same percentage in each time period, such as a population increasing by the same percentage every year.

logistic curve/logistic growth an S-shaped growth curve tending toward an upper limit.

Figure 22.3 Growth Reaching a Steady State



post-growth economy an economy that has completed the process of economic growth and operates with no further increase, and possibly a decrease, in resource and energy use.

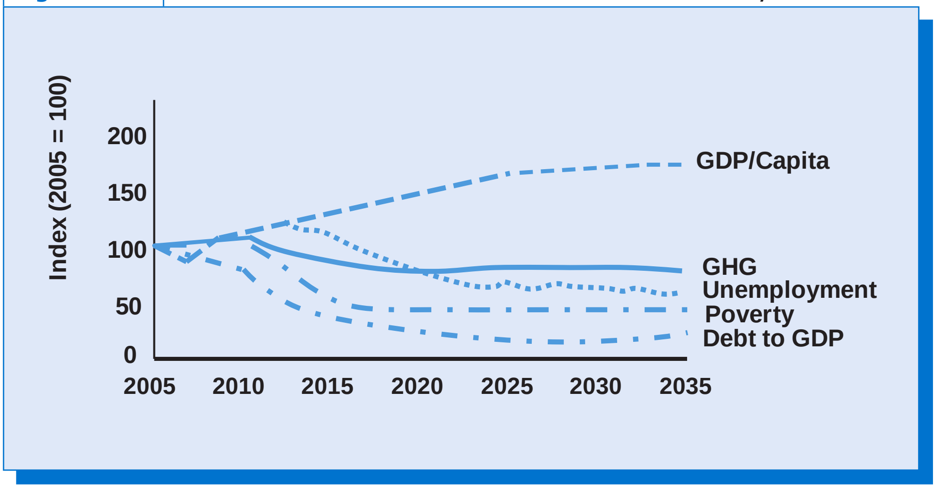
expanded goods consumption. But unregulated economic growth is unlikely to be either equitable or environmentally benign.

A global transition to more sustainable growth would involve major investments in health, water, sanitation, and education, as well as alternative energy sources and environmental protection. Currently, no national governments or international institutions are prepared to undertake such investments on anything near the necessary scale. But some theorists have proposed a **post-growth economy** that would be "slower by design, not by disaster."[29]

One model of a transition to a steady-state economy applied to the Canadian economy models "socio-eco-environmental" paths that offer attractive social and environmental outcomes without requiring continual economic growth. In the scenario presented in Figure 22.4 the Canadian government is assumed to introduce a tax on greenhouse gas (GHG) emissions, creating incentives to switch from high GHG sources of energy to lower ones, making energy in general more expensive and encouraging conservation and efficiency. The revenues from the GHG tax are used to reduce other taxes, so that the net effect on revenues is zero. In this scenario, GDP per capita stabilizes after 2025, and GHG emissions decrease by 22 percent by 2035. Poverty levels as well as unemployment decrease significantly, and fiscal balance is reached, with a steady decrease in the debt-to-GDP ratio. A shorter work week allows for full employment, with less growth in material consumption but more spending on health care and education.[30]

Such models show that slower growth, leading eventually to a steady-state economy, can be consistent with full employment, virtual elimination of poverty, more leisure, considerable reduction in GHG emissions, and fiscal balance. As noted in Chapter 14, a more environmentally-oriented economy need not result in employment losses. In fact, the achievement of sustainable development goals requires major expansion of employment in areas such as health care, education, sanitation, and renewable energy development. According to a recent study, the dedication of 1.5 percent of GDP to renewable energy development (suggested by economists as a level needed to achieve the IPCC carbon reduction targets) would result in the net creation of millions of jobs, taking into account job losses in fossil fuel industries (see Table 22.2).

Figure 22.4 A No-Growth Scenario for the Canadian Economy



Source: Adapted from Victor, 2008, pp. 182.

Note: GDP = gross domestic product; GHG = greenhouse gases.

Table 22.2 Jobs Generated Through Spending 1.5 Percent of GDP on Renewable Energy, Selected Countries

	Total Clean Energy Jobs Created through Investing 1.5% of GDP	Net Clean Energy Jobs Created after Subtracting Fossil Fuel Job Losses
Brazil	925,000	395,000
China	11.4 million	6.4 million
India	12 million	5.7 million
Indonesia	954,000	752,000
United States	1.5 million	650,000

Source: Pollin, 2015, p. 81.

Specific Policy Proposals

What specific policies would be consistent with environmentally sound development? Some of the possibilities that we have already touched on in previous chapters include:

- **Green taxes** that would shift the tax burden away from income and capital taxation and onto fossil-fuel use, resource extraction, and pollution generation. This would discourage energy- and material-intensive economic activities while favoring the provision of services and labor-intensive activities. A **revenue-neutral (tax policy)** shift could match every dollar collected in new energy and resource taxes with a dollar of income, payroll, corporate, or capital gains tax reductions.[31]

green taxes taxes based on the environmental impact of a good or service.

revenue-neutral (tax policy) term used to describe a tax policy that holds the overall level of tax revenues constant.

- Elimination of agricultural and energy subsidies that encourage overuse of energy, fertilizer, pesticides, and irrigation water. This could be matched with promotion of sustainable agricultural systems including nutrient recycling, crop diversification, and natural pest controls, minimizing the use of artificial chemicals and fertilizer.
- Greater recycling of materials and use of renewable energy. The principles of industrial ecology suggest redesigning industrial systems to imitate the closed-cycle patterns of natural systems and reuse as many materials as possible with minimal waste output.
- Efficient transportation systems that replace energy-intensive automotive transport with high-speed trains, public transit, increased bicycle use, and redesign of cities and suburbs to minimize transportation needs. The use of highly fuel-efficient cars would be important in countries such as the United States that have extensively developed automobile-centered systems. Some developing countries might avoid large-scale automobile dependence by relying instead on bicycles and efficient public transit.
- Accelerated development of **renewable energy** systems such as solar, hydroelectric, wind, and geothermal power, as well as new technologies such as fuel cells and high-efficiency industrial systems. As we saw in Chapter 11, redirection of current fossil-fuel subsidies to create market incentives for alternative energy sources is essential to this process.

renewable energy sources energy sources that are supplied on a continual basis such as wind, water, biomass, and direct solar energy.

22.5 CONCLUSION: POLICIES FOR SUSTAINABLE DEVELOPMENT

biosphere all areas on earth that contain life forms, including air, soil, land, and water.

Analysis of development policy must take long-term sustainability into account. Policies oriented toward economic growth alone risk damage to the broader "circular flow" of the **biosphere** discussed in Chapter 1, unless they include consideration of environmental impact and sustainable scale. This adds a new dimension to the debate over development policy, a dimension that will be increasingly important for both developed and developing countries.

Future sustainable paths will differ drastically between the industrialized countries of the developed world and the emerging and developing countries that are still in their growing phase, both demographically and economically.

In the Global South, the necessity to provide basic needs for hundreds of millions of poor people in rural areas and urban slums will push economic growth forward. But economic growth need not be pursued using the same growth model that has created current ecological crises. As local sustainability initiatives show, the improvement of sustainable livelihoods can be achieved without a negative effect on natural resources and the environment. A more sustainable path is conceivable for developing countries, through scaling up initiatives that combine social goals with environmental goals, including increased use of renewable energy, as well as integrated approaches to restoring soil fertility, securing access to water, and reforesting to protect biodiversity.

As the world population continues to grow, economic activity continues to expand, and the effects of climate change become more pervasive, sustainability will become both more important and more difficult to achieve. This is the major challenge of the twenty-first century, and both economic and ecological understanding will be needed to formulate global, national, and local responses.

Summary

Sustainable development has been defined as development that meets present needs without damaging the basis for meeting future needs. More broadly, sustainability can be seen as having economic, ecological, and social dimensions. The needs of a growing population must be met in an equitable fashion, without increasing resource demands and pollution generation beyond the supportive capacity of ecosystems.

For developed countries, this implies both moderation in consumption growth and adoption of more environmentally friendly technologies and renewable energy sources. Developing countries, for which growth in consumption is essential, can avoid production methods that have high resource demands and environmental repercussions. Mutual cooperation between developed and developing countries toward these goals is essential but often difficult to achieve.

Major reforms must occur in agricultural, industrial, and energy systems, as well as in renewable resource management. Low-input and organic agriculture, energy-efficient and ecologically sound industrial development, as well as better fishery and forest management, are all important components of a balanced economic/environmental system. In addition, population stabilization is central to sustainability in all these areas.

An inherent tension exists between the ideas of sustainability and economic growth. Although the two are not necessarily incompatible, we cannot have unlimited economic growth with finite resources. Future economic growth must therefore turn more toward areas such as services, communication, arts, and education that contribute to human welfare but have relatively low resource requirements.

Major global finance institutions such as the World Bank have begun to recognize the necessity of specific policy initiatives to promote more sustainable development and reorient their development lending accordingly. However, resource-intensive and pollution-generating development strategies remain common. Small-scale projects have often been successful in achieving the dual goals of poverty reduction and environmental conservation, and the challenge is to scale up these successes to national and global levels.

Sustainable development strategies attempt to balance the imperatives of economic growth with the limits of planetary resources and pollution absorption capacity. Modification of current patterns of economic growth will be essential for sustainability in the twenty-first century.

Key Terms and Concepts

agroforestry
biosphere
capital stock
critical natural capital
environmental sink functions
exponential growth
extractive reserves
green taxes
industrial ecology
logistic growth
macroeconomic scale
manufactured capital
natural capital
post-growth economy
renewable energy
revenue-neutral tax policy

steady state

strong and weak sustainability

structural adjustment

sustainable development

technological and social lock-in

Discussion Questions

1. Comment on the original definition of sustainable development: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Do you think this definition is useful, or is it so ambiguous or vague that it lacks applicability? Can you think of ways to make it more precise or alternative definitions?
2. How would you balance the goals of economic growth and environmental sustainability? To what extent are these goals necessarily in conflict?
3. Which specific policies do you think are of greatest importance in promoting environmentally sustainable development? In which areas is the world making progress toward sustainability, and where are the most serious problems?

Notes

1. The "Global North" and "Global South" are terms used to refer generally to the more economically developed countries, primarily in the Northern Hemisphere, and developing countries primarily in the Southern Hemisphere.
2. World Commission on Environment and Development, 1987.
3. See Harris *et al.*, 2001.
4. See www.imf.org and www.worldbank.org.
5. Structural adjustment policies refer to a package of conditions linked to loans to developing countries, intended to promote market-oriented economic reform. Generally, these conditions include fiscal and monetary measures aimed at balancing government budgets and restraining money supplies to avoid inflation. In addition, countries often must reduce barriers to trade, correct overvalued exchange rates, and privatize state-controlled enterprises.
6. Reed, 1997, p. 351.
7. Independent Evaluation Group, 2016.
8. World Bank, 2014; World Bank, 2016, Fiscal Year Data; The World Bank, Millennium Development Goals—Goal 7: Ensure Environmental Sustainability by 2015, http://www.worldbank.org/mdgs/environment.html.
9. World Bank, 2015.
10. World Resources Institute, 2008.
11. Global Environmental Facility, www.thegef.org/about-us and www.thegef.org/country, accessed October 2016; GEF, 2010; Heggelund *et al.*, 2005.
12. Achilleas Galatsidas and Finbar Sheehy, "What have the Millennium Goals Achieved?" *The Guardian*, July 6, 2015; United Nations, 2015, http://www.un.org/millenniumgoals/.
13. Fehling *et al.*, 2013.
14. United Nations, Sustainable Development Goals, http://www.un.org/sustainabledevelopment/sustainable-development-goals/.
15. Atisophon *et al.*, 2011.

16. UNCTAD, 2014.
17. Biermann, 2011.
18. Reuters World News, "46 Nations Call for Tougher U.N. Environment Role," Feb. 3, 2007, www.reuters.com/article/2007/02/03/usglobalwarming-appeal-idUSL0335755320070203/.
19. Examples drawn from Barnes *et al.*, 1995; Global Environmental Facility, 2012, www.thegef.org/gef/.
20. Oakland Institute, 2015; FAO, 2014; Sachamama Center for BioCultural Regeneration, www.casasangapilla.com/sachamamain/.
21. Sadhana Forest, http://sadhanaforest.org/; High Atlas Foundation, http://www.highatlasfoundation.org.
22. See World Bank, *Climate Resilient Participatory Afforestation and Reforestation Project*, http://documents.worldbank.org/curated/en/818601468014438252/Bangladesh-Climate-Resilient-Participatory-Afforestation-and-Reforestation-Project.
23. UN News Center, "UN and Partners Unveil New Initiative to Achieve Sustainable Cities," June 18, 2012, www.un.org/apps/news/story.asp?NewsID=42264#. UFObSbJIT6I/.
24. Rio+20, the United Nations Conference on Sustainable Development, also known as Earth Summit 2012, was held 20 years after the original United Nations Conference on Environment and Development held in Rio de Janeiro in 1992.
25. See http://www.c40.org/; https://www.compactofmayors.org/who-we-are/; http://www.iclei.org/; https://www.uclg.org/.
26. FAO, 2014.
27. See Daly, 1996.
28. See Harris, 2013.
29. See Jackson, 2009; Victor, 2008.
30. Victor, 2008.
31. See Metcalf, 2007 and 2015, for analysis of revenue-neutral "green" taxes.

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Web Sites

1. **www.thegef.org/** Homepage of the Global Environmental Facility. "Through its strategic investments, the GEF works with partners to tackle the planet's biggest environmental issues" as well as reducing poverty, strengthening governance, and promoting greater social equity.
2. **www.unep.org.** Web site of United Nations Environmental Program. "The United Nations Environment Programme (UNEP) is the leading global environmental authority that sets the global environmental agenda, promotes the coherent implementation of the environmental dimension of sustainable development within the United Nations system and serves as an authoritative advocate for the global environment."
3. **www.iisd.org.** The International Institute for Sustainable Development (IISD) is an independent, non-profit organization that "provides practical solutions to the challenge of integrating environmental and social priorities with economic development." Provides reports on sustainable energy, water systems management, and "green" finance and investment.
4. **www.millenniumassessment.org.** Reports by the Millennium Ecosystem Assessment, a United Nations project that "assessed the consequences of ecosystem change for human well-being," including Synthesis Reports on biodiversity, desertification, business and industry, wetlands and water, and health.
5. **www.wri.org.** Web site of the World Resources Institute, a global environmental research organization providing extensive information on climate change, energy, food, forests, water, and urban sustainability, as well as economics and finance related to better environmental management.
6. **www.iclei.org.** Web site of Local Governments for Sustainability, a Global Association of over 1500 cities, towns, and regions "committed to building a sustainable, low-carbon, resilient, ecomobile, biodiverse, resource-efficient and productive future."

Glossary

absolute water scarcity term used for situations in countries where freshwater supplies are less than 500 cubic meters per person per year. (20)

absolutely diminishing returns an increase in one or more inputs results in a decrease in output. (4)

absorptive capacity of the environment the ability of the environment to absorb and render harmless waste products. (2, 9)

adaptive measures/adaptive strategies actions designed to reduce the magnitude or risk of damages from global climate change. (12, 13)

adaptive strategies See "adaptive measures." (12)

additionality a requirement of a successful PES program; the environmental benefits must be in addition to what would have occurred without the payments. (9)

adjusted net saving (ANS) a national accounting measure developed by the World Bank which aims to measure how much a country is actually saving for its future. (10)

agroecology the application of ecological concepts to the design and management of sustainable food systems. (16)

agroforestry growing both tree and food crops on the same piece of land. (16, 22)

anthropocentric worldview a perspective that places humans at the center of analysis (1)

aquaculture the controlled cultivation of aquatic organisms, including fish and shellfish, for human use or consumption. (18)

assets something with market value, including financial assets, physical assets, and natural assets. (19)

average cost the average cost of producing each unit of a good or service; equal to total cost divided by the quantity produced. (4)

average revenue the average price a firm receives for each unit of a good or service; equal to total revenue divided by the quantity produced. (4)

average-cost pricing a water pricing strategy in which price is set equal to the average cost of production (or equal to average cost plus a profit mark-up if the water utility is a for-profit entity). (20)

avoided costs costs that can be avoided through environmental preservation or improvement. (12)

"backstop" energy technologies technologies such as solar and wind power that can replace current energy sources, especially fossil fuels. (12)

backstop resource a substitute resource that becomes a viable alternative after the price of the initial resource reaches a certain high price. (17)

beneficial use term used to refer to the use of water for productive purposes, such as irrigation or municipal supplies. (20)

benefit transfer assigning or estimating the value of a resource based on prior analysis of one or more similar resources. (7)

benefit/cost ratio total benefits divided by total costs. (7)

bequest value the value that people place on the knowledge that a resource will be available for future generations. (6)

best available control technology a pollution regulation approach in which the government mandates that all firms use a control technology deemed most effective. (8)

Better Life Index (BLI) an index developed by the OECD to measure national welfare using 11 well-being dimensions. (10)

biodiversity (biological diversity) the maintenance of many different interrelated species in an ecological community. (16, 19)

biofuels fuels derived from crops, crop wastes, animal wastes, or other biological sources. (16)

biomass an energy supply from wood, plant, and animal waste. (2, 11, 19)

biophysical cycles the circular flow of organic and inorganic materials in ecosystems. (16)

biosphere all areas on earth that contain life forms, including air, soil, land, and water. (22)

business as usual a scenario in which no significant policy, technology, or behavioral changes are expected. (12)

bycatch the harvesting of aquatic organisms other than the intended commercial species. (18)

cap and trade a tradable permit system for pollution emissions. (13)

capital depreciation a deduction in national income accounting for the wearing-out of capital over time. (9)

capital formation addition of new capital to a country's capital stock. (15)

capital shallowing a decrease in the availability of capital per worker, leading to reduced productivity per worker. (15)

capital stock the existing quantity of capital in a given region, including manufactured, human, and natural capital. (11, 22)

carbon footprint total carbon emissions, direct and indirect, resulting from the consumption of a nation, institution, or individual. (13)

carbon intensity a measure of carbon emissions per unit of GDP. (13)

carbon sinks portions of the ecosystem with the ability to absorb certain quantities of carbon dioxide, including forests and oceans. (13)

carbon tax a per-unit tax on goods and services based on the quantity of carbon dioxide emitted during the production or consumption process. (13)

carrying capacity the level of population and consumption that can be sustained by the available natural resource base. (9, 15, 16, 18)

certification the process of certifying products that meet certain standards, such as certifying produce grown using organic farming techniques. (19)

choke price the minimum price on a demand curve where the quantity demanded equals zero. (17)

Clean Water Act (CWA) the primary federal water pollution law in the United States, passed in 1972. (8)

clear-cut the process of harvesting all trees within a given area. (19)

climate justice equitable sharing both of the burdens of climate change and the costs of policy responses. (12, 13)

climate stabilization the policy of reducing fossil-fuel use to a level that would not increase the potential for global climate change. (12)

climate stabilization wedge a concept in which specific mitigation actions are presented to reduce projected global greenhouse gas emissions by one gigaton each (one gigaton reduction equals one wedge). (13)

closed system a system that does not exchange energy or resources with another system; except for solar energy and waste heat, the global ecosystem is a closed system. (9)

CO_2 equivalent (CO_2e) a measure of total greenhouse gas emissions or concentrations, converting all non-CO_2 gases to their CO_2 equivalent in warming impact. (12)

Coase theorem the proposition that if property rights are well defined and there are no transactions costs, an efficient allocation of resources will result even if externalities exist. (3)

common property resource a resource that is available to everyone (nonexcludable), but use of the resource may diminish the quantity or quality available to others (rival). (1, 4, 12, 16)

comparative advantage the theory that trade benefits both parties by allowing each to specialize in the goods that it can produce with relative efficiency. (21)

complementarity the property of being used together in production or consumption, for example, the use of gasoline and automobiles. (9)

compliance costs the cost to firms and industries of meeting pollution regulations. (14)

computable general equilibrium economic models that aim to estimate the effect of policy changes throughout an entire economy. (14)

conditionality a requirement of a successful PES program; the payments must be conditional upon a resource owner implementing changes that actually improve environmental outcomes. (9)

constant dollars an adjustment of economic time series data to account for changes in inflation. (10)

constant returns to scale a proportional increase (or decrease) in one or more inputs results in the same proportional increase (or decrease) in output. (4, 15)

consumer surplus the net benefit to a consumer from a purchase; equal to their maximum willingness to pay minus price. (3)

consumption externalities externalities associated with consumption of a good, such as pollutant emissions from vehicles. (21)

contingent ranking (CR) a survey method in which respondents are asked to rank a list of alternatives. (6)

contingent valuation (CV) an economic tool that uses surveys to question people regarding their willingness to pay for a good, such as the preservation of hiking opportunities or air quality. (6)

contraction and convergence the concept that overall environmental impacts or economic activity should be reduced at the same time that economic inequalities are reduced. (14)

cost of illness method an approach for valuing the negative impacts of pollution by estimating the cost of treating illnesses caused by the pollutant. (6)

cost-benefit analysis (CBA) a tool for policy analysis that attempts to monetize all the costs and benefits of a proposed action to determine the net benefit. (6, 7, 12, 13)

cost-effectiveness analysis a policy tool that seeks to determine the least-cost approach for achieving a given goal. (7, 13)

criteria air pollutants the six major air pollutants specified in the U.S. Clean Air Act. (8)

critical natural capital elements of natural capital for which there are no good human-made substitutes, such as basic water supplies and breathable air. (10, 22)

crop rotation and fallowing an agricultural system involving growing different crops on the same piece of land at different times and regularly taking part of the land out of production. (16)

crop value index an index indicating the relative value of production of different crops on a given quantity of land. (16)

cumulative or stock pollutant a pollutant that does not dissipate or degrade significantly over time and can accumulate in the environment, such as carbon dioxide and chlorofluorocarbons. (8, 12)

decoupling breaking the correlation between increased economic activity and similar increases in environmental impacts. (9, 14, 21)

defensive expenditures approach a pollution valuation methodology based on the expenditures households take to avoid or mitigate their exposure to a pollutant. (6)

demand-side management an approach to energy management that stresses increasing energy efficiency and reducing energy consumption. (2)

dematerialization the process of achieving an economic goal through a decrease in the use of physical materials, such as making aluminum cans with less metal. (9, 14)

demographic transition the tendency for first death rates and then birthrates to fall as a society develops economically; population growth rates first increase and eventually decrease. (15)

demonstrated reserves resources that have been identified with a high degree of confidence, and who quantity is known with some certainty. (17)

depletable resource a renewable resource that can be exploited and depleted, such as soil or clean air. (16)

depletion allowances a tax deduction for capital investments used to extract natural resources, typically oil and gas. (11)

desalination the removal of salt from ocean water to make it usable for irrigation, industrial, or municipal water supplies. (20)

diminishing returns a proportional increase (or decrease) in one or more inputs results in a smaller proportional increase (or decrease) in output. (4)

direct-use value the value one obtains by directly using a natural resource, such as harvesting a tree or visiting a national park. (6)

discount rate the annual rate at which future benefits or costs are discounted relative to current benefits or costs. (5, 7, 12, 16, 19)

discounting the concept that costs and benefits that occur in the future should be assigned less weight (discounted) relative to current costs and benefits. (7)

distortionary subsidies subsidies that alter the market equilibrium in ways that are harmful to economic efficiency. (21)

distributionally neutral tax shift a change in the pattern of taxes that leaves the distribution of income unchanged. (13)

dualistic land ownership an ownership pattern, common in developing countries, in which large landowners wield considerable power and small landowners tend to be displaced or forced onto inferior land. (21)

dynamic equilibrium a market equilibrium that results when present and future costs and benefits are considered. (5)

ecocentric worldview a perspective that places the natural world at the center of analysis (1)

ecolabeling a label on a good that provides information concerning the environmental impacts that resulted from the production of the good. (18)

ecological complexity the presence of many different living and nonliving elements in an ecosystem, interacting in complex patterns; ecosystem complexity implies that the impacts of human actions on ecosystems may be unpredictable. (9)

ecological economics a field which brings together viewpoints from different academic disciplines and views the economic system as a subset of the broader ecosystem and subject to biophysical laws. (1)

economic efficiency an allocation of resources that maximizes net social benefits; perfectly competitive markets in the absence of externalities are efficient. (3)

economic efficiency standards an environmental regulation approach that sets minimum standards for efficiency, such as electricity or fuel consumption. (11)

economic optimum a result that maximizes an economic criterion, such as efficiency or profits (18)

economic reserves (of a resource) the quantity of a resource that can be extracted profitably based on current prices and technology. (17)

economic value the value of something derived from people's willingness to pay for it. (1)

economies of scale an expanded level of output reduces per-unit production costs. (3, 15)

ecosystem services beneficial services provided freely by nature, such as flood protection, water purification, and soil formation. (6, 9)

efficiency labeling labels on goods that indicate energy efficiency, such as a label on a refrigerator indicating annual energy use. (11)

efficiency standards regulations that mandate efficiency criteria for goods, such as fuel economy standards for automobiles. (13)

elasticity of demand the sensitivity of quantity demanded to prices; an elastic demand means that a proportional increase in prices results in a larger proportional change in quantity demanded; an inelastic demand means that a proportional increase in prices results in a small change. (3)

elasticity of supply the sensitivity of quantity supplied to prices; an elastic supply means that a proportional increase in prices results in a larger proportional change in quantity supplied; an inelastic supply means that a proportional increase in prices results in a small change. (3, 16)

embodied energy the total energy required to produce a good or service, including both direct and indirect uses of energy. (9)

empty-world and full-world economics the view that economic approaches to environmental issues should differ depending on whether the scale of the economy relative to the ecosystem is small (an empty world) or large (a full world). (9)

endowment effect the concept that people tend to place high value on something after they already possess it, relative to its value before they possess it. (6)

energy demand-side management an energy policy approach that seeks to reduce energy consumption, through policies such as information campaigns or higher energy prices. (11)

energy infrastructure a system that supports the use of a particular energy source, such as the supply of gas stations and roads that support the use of automobiles. (11)

energy transition an overall shift of energy consumption away from fossil fuels toward renewable energy sources. (11)

entropy a measure of the unavailable energy in a system; according to the second law of thermodynamics, entropy increases in all physical processes. (9)

environmental asset accounts (or **natural resource accounts)** national accounts that track the level of natural resources and environmental impacts in specific categories, maintained in either physical or monetary units. (10)

environmental degradation loss of environmental resources, functions, or quality, often as a result of human economic activity. (9)

environmental economics a field of economics which applies mainstream economic principles to environmental and natural resource issues (1)

environmental justice the fair treatment of people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. (3, 12)

environmental Kuznets curve (EKC) the theory that a country's environmental impacts increase in the early stages of economic development but eventually decrease above a certain level of income. (14)

environmental sustainability the continued existence of an ecosystem in a healthy state; ecosystems may change over time but do not significantly degrade. (16)

equilibrium price the market price where the quantity supplied equals the quantity demanded. (3)

equimarginal principle the balancing of marginal costs and marginal benefits to obtain an efficient outcome. (8)

eutrophication excessive growth of oxygen-depleting plant and algal life in rivers, lakes, and oceans. (16)

Exclusive Economic Zone (EEZ) the area normally within 200 nautical miles of the coast of a country, in which that country has exclusive jurisdiction over marine resources. (18)

existence value the value people place on a resource that they do not intend to ever use, such as the benefit that one obtains from knowing an area of rain forest is preserved even though he or she will never visit it. (6)

expected value (EV) the weighted average of potential values. (7)

exponential growth a value that increases by the same percentage in each time period, such as a population increasing by the same percentage every year. (15, 22)

exponential reserve index an estimate of the availability of a mineral resource based on an assumption of exponentially increasing consumption. (17)

exported emissions/pollution shifting the impacts of pollution to other countries by importing goods whose production involves large environmental impacts. (14, 21)

external cost(s) a cost, not necessarily monetary, that is not reflected in a market transaction. (3, 16)

externalities effects of a market transaction that change the utility, positively or negatively, of those outside the transaction. (1, 15, 16)

extraction path the extraction rate of a resource over time. (17)

extractive reserves a forested area that is managed for sustainable harvests of non-timber products, such as nuts, sap, and extracts. (22)

feedback effect the process of changes in a system leading to other changes that either counteract or reinforce the original change.

feed-in tariffs a policy to provide renewable energy producers long-term contracts to purchase energy at a set price, normally based on the costs of production (but higher than the cost of production). (11)

fertility rate the average number of live births per woman in a society. (15)

first and second laws of thermodynamics physical laws stating that matter and energy cannot be destroyed, only transformed, and that all physical processes lead to a decrease in available energy (an increase in entropy). (9)

fixed factors factors of production whose quantity cannot be changed in the short run. (15)

flow the quantity of a variable measured over a period of time, including physical flows, such as the flow of a river past a given point measured in cubic feet per second, or financial flows, such as income over a period of time. (19, 20)

flow pollutants a pollutant that has a short-term impact and then dissipates or is absorbed harmlessly into the environment. (8)

food security a situation when all people have access to sufficient, safe, nutritious food to maintain a healthy and active life (16)

free market environmentalism the view that a more complete system of property rights and expanded use of market mechanisms is the best approach to solving issues of resource use and pollution control. (3)

free riders an individual or group that obtains a benefit from a public good without having to pay for it. (4)

free-rider effect the incentive for people to avoid paying for a resource when the benefits they obtain from the resource are unaffected by whether they pay; results in the undersupply of public goods. (3)

fully fished term used to describe a fish stock that is being harvested at the maximum sustainable yield. (18)

future costs and benefits benefits and costs that are expected to occur in the future, usually compared to present costs through discounting. (12)

gains from trade the net social benefits that result from trade. (21)

GDP growth rate the annual change in GDP, expressed as a percentage. (2)

General Agreement on Tariffs and Trade (GATT) a multilateral trade agreement providing a framework for the gradual elimination of tariffs and other barriers to trade; the predecessor to the World Trade Organization. (21)

General Mining Act of 1872 a U.S. federal law that regulates mining for economic minerals on federal lands. (17)

genuine progress indicator (GPI) a national accounting measure that includes the monetary value of goods and services that contribute to well-being, such as volunteer work and higher education, and deducts impacts that detract from well-being, such as the loss of leisure time, pollution, and commuting. (10)

global carbon budget the concept that total cumulative emissions of carbon must be limited to a fixed amount in order to avoid catastrophic consequences of global climate change. (13)

global climate change the changes in global climate, including temperature, precipitation, storm frequency and intensity, and changes in carbon and water cycles, that result with increased concentrations of greenhouse gases in the atmosphere. (12)

global commons global common property resources such as the atmosphere and the oceans. (4, 12)

global pollutant pollutants that can cause global impacts, such as carbon dioxide and chlorofluorocarbons. (8)

global warming the increase in average global temperature as a result of emissions from human activities. (12)

government procurement programs that guarantee a certain government demand for a good or service. (17)

grandfathering the process of exempting existing industrial facilities from complying with new environmental standards or regulations. (8)

green economy an economy that improves human well-being and social equity, while reducing environmental impacts. (14)

Green GDP a national accounting measure that deducts a monetary value from GDP or NDP to account for natural capital depreciation and other environmental damages. (10)

green taxes taxes based on the environmental impact of a good or service. (22)

greenhouse development rights (GDR) an approach for assigning the responsibility for past greenhouse gas emissions and the capability to respond to climate change. (13)

greenhouse effect the effect of certain gases in the earth's atmosphere trapping solar radiation, resulting in an increase in global temperatures and other climatic impacts. (12)

greenhouse gases gases such as carbon dioxide and methane whose atmospheric concentrations influence global climate by trapping solar radiation. (12)

gross annual population increase the total numerical increase in population for a given region over one year. (15)

gross domestic product (GDP) the total market value of all final goods and services produced within a national border in a year. (2, 10)

gross national happiness (GNH) the concept, originating in Bhutan, where a society and its policies should seek to improve the welfare of its citizens, as opposed to maximizing GDP. (10)

gross national product (GNP) the total market value of all final goods and services produced by citizens of a particular country in a year, regardless of where such production takes place. (10)

habitat equivalency analysis (HEA) a method used to compensate for the damages from a natural resource injury with an equivalent amount of habitat restoration. (6)

harmonization of environmental standards the standardization of environmental standards across countries, as in the European Union. (21)

Hartwick rule a principle of resource use stating that resource rents—the proceeds of resource sale, net of extraction costs—should be invested rather than consumed. (5)

hedonic pricing the use of statistical analysis to explain the price of a good or service as a function of several components, such as explaining the price of a home as a function of the number of rooms, the caliber of local schools, and the surrounding air quality. (6)

holdout effect the ability of a single entity to hinder a multiparty agreement by making disproportionate demands. (3)

Hotelling's rule a theory stating that in equilibrium the net price (price minus production costs, or the scarcity rent) of a resource must rise at a rate equal to the rate of interest. (5, 17)

hotspots locally high levels of pollution, for example, surrounding a high-emitting plant; hotspots can occur under a pollution trading scheme. (8)

Hubbert curve a bell-shaped curve showing the production quantity of a nonrenewable energy resource over time. (11)

Human Development Index (HDI) a national accounting measure developed by the United Nations, based on three factors GDP levels, education, and life expectancy. (10)

hydrologic cycle the natural purification of water through evaporation and precipitation. (20)

hydropower the generation of electricity from the energy in flowing water. (11)

hypothetical and speculative reserves the quantity of a resource that is not identified with certainty but is hypothesized to exist. (17)

identified reserves the quantity of a resource that has been identified with varying degrees of confidence; includes both economic and subeconomic reserves. (17)

identity a mathematical statement that is true by definition. (15)

income inequality a distribution of income in which some portions of the population receive much greater income than others. (15)

indirect-use value ecosystem benefits that are not valued in markets, such as flood prevention and pollution absorption. (6)

individual transferable quotas (ITQs) tradable rights to harvest a resource, such as a permit to harvest a particular quantity of fish. (4, 18)

induced innovation innovation in a particular industry resulting from changes in the relative prices of inputs. (16)

industrial ecology the application of ecological principles to the management of industrial activity. (14, 22)

inferred reserves resources that have been identified with a low degree of confidence, and whose quantity is not known with certainty. (17)

inflection point the point on a curve where the second derivative equals zero, indicating a change from positive to negative curvature or vice versa. (18)

information asymmetry a situation in which different agents in a market have different knowledge or access to information. (16)

information-intensive techniques production techniques that require specialized knowledge; usually these techniques substitute knowledge for energy, produced capital, or material inputs, often reducing environmental impacts. (16)

inherent value the value of something separate from economic value, based on ethics, rights, and justice. (1)

integrated pest management (IPM) the use of methods such as natural predators, crop rotations, and pest removal to reduce pesticide application rates. (16)

intercropping an agricultural system involving growing two or more crops together on a piece of land at the same time. (16)

intergenerational equity the distribution of resources, including human-made and natural capital, across human generations. (9)

intermittency a characteristic of energy sources such as wind and solar, which are available in different amounts at different times. (11)

internalizing external costs/externalities using approaches such as taxation to incorporate external costs into market decisions. (3)

irreversibility the concept that some human impacts on the environment may cause damage that cannot be reversed, such as the extinction of species. (9)

labor-intensive techniques production techniques that rely heavily on labor input. (16)

law of demand the economic theory that the quantity of a good or service demanded will decrease as the price increases. (3)

law of diminishing returns the principle that a continual increase in production inputs will eventually yield decreasing marginal output. (15)

law of supply the economic theory that the quantity of a good or service supplied will increase as the price increases. (3)

Law of the Sea a 1982 international treaty regulating marine fisheries. (18)

leakage a requirement of a successful PES program is avoiding leakage; the environmentally-beneficial actions a resource owner takes must not be offset by other changes that are environmentally detrimental. (9)

least-cost options actions that can be taken for the lowest overall cost. (12)

levelized costs the per-unit cost of energy production, accounting for all fixed and variable costs over a power source's lifetime. (11)

license fee the fee paid for access to a resource, such as a fishing license. (4)

local and regional air pollutants pollutants that cause adverse impacts only within the area where they are emitted. (8)

logistic curve/logistic growth an S-shaped growth curve tending toward an upper limit. (18, 19, 22)

luxury good a good that people tend to spend a higher percentage of their income on as their incomes increase. (14)

macroeconomic scale the total scale of an economy; ecological economics suggests that the ecosystem imposes scale limits on the macroeconomy. (22)

Malthusian hypothesis the theory proposed by Thomas Malthus in 1798 that population would eventually outgrow available food supplies. (2, 16)

manufactured capital productive resources produced by humans, such as factories, roads, and computers, also referred to as produced capital or human-made capital. (22)

marginal abatement costs costs of reduction for one extra unit of pollution, such as carbon emissions. (12)

marginal benefit the benefit of producing or consuming one more unit of a good or service. (3, 4)

marginal cost the cost of producing one more unit of a good or service. (3, 4)

marginal net benefit the net benefit of the consumption or production of an additional unit of a resource; marginal net benefits are equal to marginal benefits minus marginal costs. (5)

marginal physical product the additional quantity of output produced by increasing an input level by one unit. (16)

marginal revenue the additional revenue obtained by selling one more unit of a good or service. (4)

marginal revenue product the additional revenue obtained by increasing an input level by one unit; equal to marginal physical product multiplied by marginal revenue. (16)

market equilibrium the market outcome where the quantity demanded equals the quantity supplied. (3)

market failure situations in which an unregulated market fails to produce an outcome that is the most beneficial to society as a whole. (1, 15, 18)

market-based pollution control pollution regulations based on market forces without specific control of firm-level decisions, such as taxes, subsidies, and permit systems. (8)

materials substitution changing the materials used to produce a product, such as using plastic pipe instead of copper in plumbing systems. (14)

maximum sustainable yield (MSY) the maximum quantity of a natural resource that can be harvested annually without depleting the stock or population of the resource. (18)

mean annual increment (MAI) the average growth rate of a forest; obtained by dividing the total weight of timber by the age of the forest. (19)

meta-analysis an analysis method based on a quantitative review of numerous existing research studies to identify the factors that produce differences in results across studies. (6)

methodological pluralism the view that a more comprehensive understanding of problems can be obtained using a combination of perspectives. (9)

micro-irrigation irrigation systems that increase the efficiency of water use by applying water in small quantities close to the plants. (20)

micronutrients nutrients present in low concentrations in soil, required for plant growth or health. (16)

monoculture an agricultural system involving the growing of the same crop exclusively on a piece of land year after year. (16, 18, 19)

multilateral environmental agreements (MEAs) international treaties between countries on environmental issues, such as the Convention on Trade in Endangered Species. (21)

multiple cropping an agricultural system involving growing more than one crop on a piece of land in the same year. (16)

nationally determined contribution (NDC) a voluntary planned reduction in CO_2 emissions, relative to baseline emissions, submitted by participating countries at the Paris Conference of the Parties (COP-21) in 2015. (13)

natural capital depreciation a deduction in national accounting for loss of natural capital, such as a reduction in the supply of timber, wildlife habitat, or mineral resources, or environmental degradation such as pollution. (9, 10)

natural capital the available endowment of land and resources, including air, water, soil, forests, fisheries, minerals, and ecological life-support systems. (2, 10, 15, 22)

natural capital sustainability conserving natural capital by limiting depletion rates and investing in resource renewal. (9)

natural resource limitations constraints on production resulting from limited availability of natural resources. (15)

natural resources the endowment of land and resources, including air, water, soil, forests, fisheries, minerals, and ecological life-support systems. (1)

negative externality negative impacts of a market transaction affecting those not involved in the transaction. (3)

neo-Malthusian perspective the modern version of Thomas Malthus's argument that human population growth can lead to catastrophic ecological consequences and an increase in the human death rate. (15)

net benefits total benefits minus total costs. (7)

net domestic product (NDP) gross domestic product minus the value of depreciation of produced, or human-made, capital. (10)

net domestic saving a national accounting measure equal to gross domestic saving less manufactured capital depreciation. (10)

net investment and disinvestment the process of adding to, or subtracting from, productive capital over time, calculated by subtracting depreciation from gross, or total, investment. (9)

net present value (NPV) present value of benefits minus present value of costs. (7)

net price (of a resource) the price of a resource minus production costs. (17)

net primary product of photosynthesis (NPP) the biomass energy directly produced by photosynthesis. (9)

nitrogen cycle the conversion of nitrogen into different forms in the ecosystem, including the fixation of nitrogen by symbiotic bacteria in certain plants such as legumes. (16)

nominal GDP gross domestic product measured using current dollars. (2)

nonexcludable good a good that is available to all users, under conditions in which it is impossible, or at least difficult, to exclude potential users. (4)

nonlinear or threshold effects pollution damages that are not linearly correlated with pollution levels. (8)

nonmarket benefits benefits not obtained from goods and services sold in markets. (6)

nonpoint-source pollution pollution that is difficult to identify as originating from a particular source, such as groundwater contamination from agricultural chemicals used over a wide area. (8, 16)

nonrenewable resources resources that do not regenerate through ecological processes, at least on a human time scale, such as oil, coal, and mineral ores. (1, 5, 17)

nonrenewable stock See "nonrenewable resources." (11)

non-response bias bias as a result of survey respondents not being representative of survey non-respondents. (6)

nonrival good a good whose use by one person does not limit its use by others; one of the two characteristics of public goods. (4)

nonuniformly mixed pollutants pollutants that cause different impacts in different areas, depending on where they are emitted. (8)

nonuse values values that people obtain without actually using a resource (i.e., psychological benefits); nonuse values include existence, option, and bequest values. (6)

normal good a good for which total expenditures tend to increase as income increases. (14)

nutrient recycling the ability of ecological systems to transform nutrients such as carbon, nitrogen, and phosphorus into different chemical forms. (16)

nutritional deficit the failure to meet human demands for basic levels of nutrition. (16)

ocean acidification increasing acidity of ocean waters as a result of dissolved carbon from CO_2 emitted into the atmosphere. (12)

open system a system that exchanges energy or natural resources with another system; the economic system is considered an open system because it receives energy and natural resources from the ecosystem and deposits wastes into the ecosystem. (9)

open-access equilibrium the level of use of an open-access resource that results from a market with unrestricted entry; this level of use may lead to depletion of the resource. (4)

open-access resource(s) a resource that offers unrestricted and unregulated access such as an ocean fishery or the atmosphere. (4, 18)

optimal depletion rate the depletion rate for a natural resource that maximizes the net present value of the resource. (5)

optimal level of pollution the pollution level that maximizes net social benefits. (3, 8)

optimal macroeconomic scale the concept that economic systems have an optimal scale level beyond which further growth leads to lower well-being or resource degradation. (9)

optimum rotation period the rotation period for a renewable resource that maximizes the financial gain from harvest; determined by maximizing the discounted difference between total revenues and total costs. (19)

option value the value that people place on the maintenance of future options for resource use. (6)

overfished term used to describe a fish stock that is being harvested beyond the maximum sustainable yield. (18)

overfishing a level of fishing effort that depletes the stock of a fishery over time. (4)

payments for ecosystem services (PES) payments provided to natural resource owners in exchange for sustainable management practices. (9, 19)

per capita GDP growth rate the annual change in per capita GDP, expressed as a percentage. (2)

per capita output the total product of a society divided by population. (15)

permanence a requirement of a successful PES program; the environmental benefits must persist for the long-term. (9)

permit auction a system that allocates pollution permits to the highest bidders. (8)

physical accounting a supplement to national income accounting that estimates the stock or services of natural resources in physical, rather than economic, terms. (9)

physical reserves (of a resource) the total quantity of a resource that is available, without taking into account the economic feasibility of extraction. (17)

Pigovian (pollution) tax a per-unit tax set equal to the external damage caused by an activity, such as a tax per ton of pollution emitted equal to the external damage of a ton of pollution. (3, 8)

pluralism the perspective that a full understanding of an issue can only come from a variety of viewpoints, disciplines, and approaches. (1)

point-source pollution pollution that is emitted from an identifiable source such as a smokestack or waste pipe. (8)

polluter pays principle the view that those responsible for pollution should pay for the associated external costs, such as health costs and damage to wildlife habitats. (3)

pollution haven a country or region that attracts high-polluting industries due to low levels of environmental regulation. (21)

pollution (or emissions) standards a regulation that mandates firms or industries to meet a specific pollution level or pollution reduction. (8)

pollution tax(es) a per-unit tax based on the level of pollution. (13)

population age profile an estimate of the number of people within given age groups in a country at a point in time. (15)

population biology the study of how the population of a species changes as a result of environmental conditions. (18)

population cohort the group of people born within a specific period in a country. (15)

population growth rate the annual change in the population of a given area, expressed as a percentage. (2, 15)

population momentum the tendency for a population to continue to grow, even if the fertility rate falls to the replacement level, as long as a high proportion of the population is in young age cohorts. (15)

Porter hypothesis the theory that environmental regulations motivate firms to identify cost-saving innovations that otherwise would not have been implemented. (14)

positional analysis a policy analysis tool that combines economic valuation with other considerations such as equity, individual rights, and social priorities; it does not aim to reduce all impacts to monetary terms. (7)

positive externality the positive impacts of a market transaction that affect those not involved in the transaction. (3)

post-growth economy an economy that has completed the process of economic growth and operates with no further increase, and possibly a decrease, in resource and energy use. (22)

precautionary principle the view that policies should account for uncertainty by taking steps to avoid low-probability but catastrophic events. (7, 8, 9, 12, 18, 21)

present value the current value of a stream of future costs or benefits; a discount rate is used to convert future costs or benefits to present values. (5, 7, 11, 16)

preventive measures/preventive strategies actions designed to reduce the extent of climate change by reducing projected emissions of greenhouse gases. (12, 13)

price elasticity of demand the responsiveness of the quantity demanded to price, equal to the percentage change in quantity demanded divided by the percentage change in price. (3, 20)

price elasticity of supply the responsiveness of the quantity supplied to price, equal to the percentage change in quantity supplied divided by the percentage change in price. (3)

price path the price of a resource, typically a nonrenewable resource, over time. (17)

price taker a seller in a competitive market who has no control over the price of the product. (17)

price volatility rapid and frequent changes in price, leading to market instability. (13, 16)

prior appropriation water rights a system of water rights allocation in which rights are not based on land ownership but on established beneficial uses. (20)

process and production methods (PPMs) international trade rules stating that an importing country cannot use trade barriers or penalties against another country for failure to meet environmental or social standards related to the process of production. (21)

producer surplus the net benefits of a market transaction to producers, equal to the selling price minus production costs (i.e., profits). (3)

production externalities externalities associated with the production of a good or service, such as emissions of pollutants from a factory. (21)

profits total revenue received minus total cost to producers. (4)

progressive taxes taxes that comprise a higher share of income with higher income levels. (13)

protest bids responses to contingent valuation questions based on the respondent's opposition to the question or the payment vehicle, rather than the underlying valuation of the resource. (6)

proxy variable a variable that is meant to represent a broader concept, such as the use of fertilizer application rates to represent the input-intensity of agricultural production. (16)

public goods goods that are available to all and whose use by one person does not reduce their availability to others. (1, 4, 12)

purchasing power parity (PPP) an adjustment to GDP to account for differences in spending power across countries.

pure rate of time preference the rate of preference for obtaining benefits now as opposed to the future, independent of income level changes. (7)

quota/quota system a system of limiting access to a resource through restrictions on the permissible harvest of the resource. (4)

"race to the bottom" the tendency for countries to weaken national environmental standards to attract foreign businesses or to keep existing businesses from moving to other countries. (21)

range bias a potential bias with payment card or multiple-bounded contingent valuation questions whereby the responses are influenced by the range of values presented to the respondent. (6)

real GDP gross domestic product corrected for inflation using a price index. (2, 10)

real or **inflation-adjusted dollars** monetary estimates that account for changes in price levels (i.e., inflation) over time. (7)

Reduction of Emissions from Deforestation and Degradation (REDD) a United Nations program adopted as part of the Kyoto process of climate negotiations, intended to reduce emissions from deforestation and land degradation through providing funding for forest conservation and sustainable land use. (13)

referendum format a contingent valuation question format where the valuation question is presented as a vote on a hypothetical referendum. (6)

regressive tax a tax in which the rate of taxation, as a percentage of income, decreases with increasing income levels. (13)

regulated monopolies monopolies that are regulated by an external entity, for example through controls on price or profits. (20)

relative and absolute decoupling breaking the correlation between increased economic activity and increases in environmental impacts; in absolute decoupling, an increase of economic activity is associated with a decrease in environmental impacts. (14)

renewable energy sources energy sources that are supplied on a continual basis, such as wind, water, biomass, and direct solar energy. (22)

renewable energy targets regulations that set targets for the percentage of energy obtained from renewable energy sources. (11)

renewable flow the continuous quantity of a renewable energy source supplied over time, such as the quantity of solar energy available each year. (11)

renewable resources resources that are regenerated over time through ecological processes, such as forests and fisheries, but can be depleted through exploitation. (1, 5, 16, 18)

replacement cost methods an approach to measuring environmental damages that estimates the costs necessary to restore or replace the resource, such as applying fertilizer to restore soil fertility. (6)

replacement fertility level the fertility level that would result in a stable population. (15)

resilience the capacity of ecosystem to recover from adverse impacts. (18, 19)

resistant pest species pest species which evolve resistance to pesticides, requiring either higher pesticide application rates or new pesticides to control the species. (16)

Resource Conservation and Recovery Act (RCRA) the primary federal U.S. law regulating the disposal of hazardous waste. (8)

resource curse hypothesis the theory that countries or regions with abundant natural resources actually grow more slowly than those where natural resources are scarcer. (2)

resource depletion a decline in the stock of a renewable resource due to human exploitation. (9)

resource depletion tax a tax imposed on the extraction or sale of a natural resource. (5)

resource lifetime an estimate of how long a nonrenewable resources is expected to last given assumptions about prices, technology, and depletion rates. (17)

resource substitution/substitutability the use of one resource in a production process as a substitute for another resource, such as the use of aluminum instead of copper in electrical wiring. (17)

resource use profile the consumption rates for a resource over time, typically applied to nonrenewable resources. (17)

revealed preference methods methods of economic valuation based on market behaviors, including travel cost models, hedonic pricing, and the defensive expenditures approach. (6)

revenue-neutral (tax policy) term used to describe a tax policy that holds the overall level of tax revenues constant. (8, 22)

revenue-neutral tax shift policies that are designed to balance tax increases on certain products or activities with a reduction in other taxes, such as a reduction in income taxes that offsets a carbon-based tax. (13)

riparian water rights a system of water rights allocation based on adjacent land ownership. (20)

risk term used to describe a situation in which all potential outcomes and their probabilities are known or can be accurately estimated. (7)

risk aversion the tendency to prefer certainty instead of risky outcomes, particularly in cases when significant negative consequences may result from an action. (7)

rival good a good whose use by one person diminishes the quantity or quality of the good available to others. (4)

safe minimum standard the principle that environmental policies on issues involving uncertainty should be set to avoid possible catastrophic consequences. (7)

salinization and alkalinization of soils the buildup of salt or alkali concentrations in soil from the evaporation of water depositing dissolved salts, with the effect of reducing the productivity of the soil. (16)

satellite accounts accounts that estimate the supply of natural capital in physical, rather than monetary, terms; used to supplement traditional national income accounting. (9)

scale limit a limit to the size of a system, including an economic system. (9)

scale, composition, and technique effects the impacts of trade on economic growth, industrial patterns, and technological progress; the combination of effects may be environmentally negative, positive, or neutral. (21)

scarcity rent payments to resource owners in excess of the amount necessary to keep those resources in production. (5, 17)

second law of thermodynamics the physical law stating that all physical processes lead to a decrease in available energy, that is, an increase in entropy. (17)

second-best solution a policy solution to a problem that fails to maximize potential net social benefits, but that may be desirable if the optimal solution cannot be achieved. (21)

secure property rights clearly defined and legally binding rights of property ownership. (19)

sensitivity analysis an analytical tool that studies how the outputs of a model change as the assumptions of the model change. (7)

shortage a market situation in which the quantity demanded exceeds the quantity supplied. (3)

side agreement a provision related to a trade treaty dealing with social or environmental issues. (21)

siltation pollution of water caused by increased concentration of suspended sediments. (16)

sink function the ability of natural environments to absorb wastes and pollution. (8, 18, 22)

smelting the production of a metal from a metallic ore. (17)

social benefits the market and nonmarket benefits associated with a good or service aggregated across all members of a society. (4)

social cost of carbon an estimate of the financial cost of carbon emissions per unit, including both present and future costs. (13)

social cost the market and nonmarket costs associated with a good or service. (5)

social discount rate/social rate of time preference (SRTP) a discount rate that attempts to reflect the appropriate social valuation of the future. (7)

social marginal cost curve the cost of providing one more unit of a good or service, considering both private production costs and externalities. (3)

socially efficient a market situation in which net social benefits are maximized. (3)

solar energy the energy supplied continually by the sun, including direct solar energy as well as indirect forms such as wind energy and flowing water. (11)

solar flux the continual flow of solar energy to the earth. (9, 15)

source function the ability of the environment to make services and raw materials available for human use. (18)

species diversity see **biodiversity**

specificity rule the view that policy solutions should be targeted directly at the source of a problem. (21)

stable equilibrium an equilibrium, for example of the stock level of a renewable resource, to which the system will tend to return after short-term changes in conditions affecting stock level of the resource. (18)

standard circular flow model a diagram that illustrates the ways goods, services, capital, and money flows between households and businesses. (1)

stated preference methods economic valuation methods based on survey responses to hypothetical scenarios, including contingent valuation and contingent ranking. (6)

static equilibrium a market equilibrium that results when only present costs and benefits are considered. (5)

static reserve index an index that divides the economic reserves of a resource by the current rate of use for the resource. (17)

steady state an economy that maintains a constant level of natural capital by limiting the throughput of material and energy resources. (9, 22)

stock the quantity of a variable at a given point in time, such as the amount of water in a lake, or the amount of timber in a forest, at a given time. (19, 20)

strategic bias/strategic behavior the tendency for people to state their preferences or values inaccurately in order to influence policy decisions. (6)

strong sustainability the view that natural and human-made capital are generally not substitutable and, therefore, natural capital levels should be maintained. (9, 10, 22)

structural adjustment policies to promote market-oriented economic reform in developing countries by making loans conditional on reforms such as controlling inflation, reducing trade barriers, and privatization of businesses. (22)

subeconomic resources term used to describe mineral resources that cannot be profitably extracted with current technology and prices. (17)

subsidy government assistance to an industry or economic activity; subsidies can be direct, through financial assistance, or indirect, through other beneficial policies. (3)

substitutability (of human-made and natural capital) the ability of one resource or input to substitute for another; in particular, the ability of human-made capital to compensate for the depletion of some types of natural capital. (9)

supply constraint an upper limit on supply, for example, of a nonrenewable resource. (5)

surplus a market situation in which the quantity supplied exceeds the quantity demanded. (3)

sustainable agriculture systems of agricultural production that do not deplete the productivity of the land or environmental quality, including such techniques as integrated pest management, organic techniques, and multiple cropping. (16)

sustainable development development that meets the needs of the present without compromising the ability of future generations to meet their own needs. (1, 22)

sustainable (natural resource) management management of natural resources such that natural capital remains constant over time, including maintenance of both stocks and flows. (18, 19)

sustainable yield a yield or harvest level that can be maintained without diminishing the stock or population of the resource. (9)

System of Environmental-Economic Accounting (SEEA) a framework developed by the United Nations and other international organizations to provide standards for incorporating natural capital and environmental quality into national accounting systems. (10)

tailings the unwanted material from mining operations, often highly toxic. (17)

technological and social lock-in dependence on a particular technology or accepted system of production and consumption. (17, 22)

technological lock-in the tendency of an industry or society to continue to use a given technology despite the availability of more efficient or cheaper technologies. (17)

technological progress increases in knowledge used to develop new products or improve existing products. (15)

technology transfer the process of sharing technological information or equipment, particularly among countries. (13)

technology-based regulation pollution regulation by requiring firms to implement specific equipment or actions. (8)

theoretical paradigm the basic conceptual approach used to study a particular issue. (2)

throughput the total use of energy and materials as both inputs and outputs of a process. (9, 14)

total cost the total cost to a firm of producing its output. (4)

total economic value the value of a resource considering both use and nonuse values. (6, 19)

total net benefit total benefit minus total cost. (5)

total product the total quantity of a good or service produced with a given quantity of inputs. (4, 18)

total revenue the total revenue obtained by selling a particular quantity of a good or service; equal to price per unit multiplied by quantity sold. (4)

toxic air pollutants harmful air pollutants other than the six criteria pollutants, as specified in the U.S. Clean Air Act. (8)

Toxic Substances Control Act (TSCA) the primary federal U.S. law regulating the use and sale of toxic chemicals. (8)

tragedy of the commons the tendency for common property resources to be overexploited because no one has an incentive to conserve the resource while individual financial incentives promote expanded exploitation. (4, 18)

transaction costs costs associated with a market transaction or negotiation, such as legal and administrative costs to transfer property or to bring disputing parties together. (3)

transferable (tradable) permits permits that allow a firm to emit a certain quantity of pollution. (8, 13)

travel cost models (TCMs) use statistical analysis to determine people's willingness to pay to visit a natural resource such as a national park or river; a demand curve for the resource is obtained by analyzing the relationship between visitation choices and travel costs. (6)

uncertainty term used to describe a situation in which some of the outcomes of an action are unknown or cannot be assigned probabilities. (7)

underfished term used to describe a fish stock that is being harvested below the maximum sustainable yield. (18)

uniformly mixed pollutants any pollutant emitted by many sources in a region resulting in relatively constant concentration levels across the region. (8)

unstable equilibrium a temporary equilibrium, for example, of the stock level of a renewable resource, that can be altered by minor changes in conditions, resulting in a large change in stock levels. (18)

upstream policy a policy to regulate emissions or production as near as possible to the point of natural resource extraction. (8)

upstream tax a tax implemented as near as possible to the point of natural resource extraction. (3)

use values the value that people place on the tangible or physical benefits of a good or service. (6)

user costs opportunity costs associated with the loss of future potential uses of a resource, resulting from consumption of the resource in the present. (5, 17)

value-added method the additional value of a good or service from each step in the production process. (10)

value of a statistical life (VSL) the willingness to pay of society to avoid one death based on valuations of changes in the risk of death. (7)

vertical addition adding the price of more than one demand curve at the same quantity demanded. (4)

virgin resource a resource obtained from nature, as opposed to using recycled materials. (17)

virtual water water embedded in goods or services, based on water used as an input throughout the production process. (20)

wage-risk analysis a method used to estimate the value of a statistical life based on the required compensation needed to entice people to high-risk jobs. (7)

water footprint the total amount of water consumed by a human entity—individual, family, city, corporation, or country—whether directly or indirectly, calculated by summing all the virtual water embedded in the products, energy, and services used by this entity. (20)

water markets mechanism to sell water or water rights to potential buyers. (20)

water pricing setting the price of water to influence the quantity consumed. (20)

water privatization the management of water resources by a private for-profit entity as opposed to a public utility. (20)

water scarce term used for countries where freshwater supplies are less than 1,000 cubic meters per person per year. (20)

water security sustainable access to adequate quantities of acceptable quality water to sustain human well-being and socio-economic development (16)

water stressed term used for countries where freshwater supplies are between 1,700 and 1,000 cubic meters per person per year. (20)

watershed restoration restoring natural watershed functions through the management of small-scale water cycles. (20)

weak sustainability the view that natural capital depletion is justified as long as it is compensated for with increases in human-made capital; assumes that human-made capital can substitute for most types of natural capital. (9, 10, 22)

welfare analysis an economic tool that analyzes the total costs and benefits of alternative policies to different groups, such as producers and consumers. (3)

willingness to accept (WTA) the minimum amount of money people would accept as compensation for an action that reduces their well-being. (6)

willingness to pay (WTP) the maximum amount of money people are willing to pay for a good or service that increases their well-being. (3, 6)

World Environmental Organization (WEO) a proposed international organization that would have oversight of global environmental issues. (21)

World Trade Organization (WTO) an international organization dedicated to the expansion of trade through lowering or eliminating tariffs and nontariff barriers to trade. (21)

WTO's Article XX a World Trade Organization rule allowing countries to restrict trade in order to conserve exhaustible natural resources or to protect human, animal, or plant life or health. (21)

yea-saying responding "yes" to a contingent valuation WTP question even though one's true valuation of the scenario is less, for reasons such as perceiving "yes" to be a correct answer. (6)

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Entries in **bold** denote boxes and tables; entries in *italics* denote figures.