FOOD SECURITY AND CLIMATE CHANGE IN THE NILE BASIN: THE IMPLICATIONS OF TRANSBOUNDARY WATER USE EXTERNALITY

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Abstract

The impact of climate change on food security in the Nile basin is evaluated using a multi-country, multi-sector computable general equilibrium model. The analysis employs the GTAP 10 database and the GTAP-W model that differentiates between rainfed and irrigated agriculture. The economy-wide impact of climate change in 2050 is evaluated for the B1 global emissions scenario from two global circulation models (CSIRO and MIROC). The study applies two scales of analysis – riparian and basin-scale analysis. The results reveal that climate change induces adverse effects on the state of food security in the basin through its impact on the 'food availability' and 'access to food' dimensions of food security. The results unequivocally disclose that the basin-scale analysis that underpins basin-wide cooperative and efficient management of the water and other resources of the Nile basin, with water use externalities internalized provides a significant opportunity to better absorb climate shocks compared to the riparian-scale analysis.

Keywords: Climate change; Food security; Computable General Equilibrium Model; Nile basin

1. Introduction

Food security remains one of the major development challenges in the Nile basin (NBI, 2020; Omiti et al., 2019), and lack of access to food at the individual or household level is widespread (Nashwael-Tatatwy and Elbahai, 2018). The extent of moderate or severe food insecurity in the basin ranges from 28.5 percent of the total population in Egypt to a staggering 87.3 percent in South Sudan, with the figures for the remaining countries varying from 51.8 to 74.2 percent (FAO et al., 2023). Moreover, hunger is at a serious or alarming rate in all the Nile basin countries except Egypt, where hunger stands at a moderate level (von Grebmer et al., 2022). Besides, the prevalence of undernourishment, particularly in upstream countries, is significant, with the proportion of the affected population ranging from 21.4 percent in South Sudan to 31.6 percent in Rwanda and Uganda (FAO et al., 2023). The undernourished population in Ethiopia, Kenya, and Tanzania accounts for 21.9, 27.8, and 23.5 percent of the total population, respectively (FAO et al., 2023). Downstream countries Egypt and Sudan fare relatively better, with only 7.2 and 11.9 percent of their population, respectively, undernourished.

Uncertainties related to future climate change pose additional challenges for agriculture and food security in the Nile basin. Changes in temperature and rainfall patterns induced by climate change and the resultant impacts on water availability and extreme weather events will substantially affect the potential for agricultural production. Climate change will inevitably result in higher evaporation rates and water demands in the Nile basin (Conway, 2005), thereby increasing crop water requirements and reducing agricultural yields (Blackmore and Whittington, 2008). The Nile basin is sensitive to climate change (Elshamy et al. 2009; Beyene et al. 2010), which is expected to have profound repercussions on agricultural production and overall economic conditions, thereby compounding the already deplorable food security situation in the basin.

Irrigation development could serve as an adaptation mechanism to alleviate the adverse food security implications of climate change in the basin. Accordingly, both upstream and downstream countries are considering a substantial expansion in irrigation (Awulachew et al., 2012) that cannot be supported by the total annual flows of the Nile River. Such a unilateral move will further aggravate the already severe water use externalities in the basin, where prior water resource development in downstream countries has imposed constraints on upstream water development, and potential significant upstream water resource abstraction threatens the water supply downstream. Thus, water use externalities in the Nile basin involve serious tradeoffs in economic opportunity between upstream and downstream countries and constitute a major water resource development challenge in the basin, which is expected to intensify over time with climate change.

In light of the foregoing issues, an important policy-relevant research question worth considering is how internalizing the existing water use externalities in the Nile basin would affect the state of food security in the basin under climate change. That is, would internalizing water use externalities in the basin improve the basin's capacity to absorb climate shocks compared to the status quo? The significance of internalizing water use externalities in the basin is evaluated using two scales of analysis: riparian – and basin-scale. The riparian-scale analysis (i.e., the status quo) considers each riparian country separately based on political boundaries, where water use by one country reduces what is available for the others. The basin-scale analysis recognizes the basin as an appropriate unit of water resource management and involves aggregating all the Nile basin countries into a single region, treating them as if they are a single country in terms of their resource management, thereby internalizing existing water use externalities in the basin. This is a reasonable assumption given all the Nile basin countries except Tanzania are already members of the Common Market for Eastern and Southern Africa (COMESA) that facilitates free movement of factors between member countries and liberalizes labour mobility and investment across borders besides to the reductions of trade barriers. The basin-scale analysis envisions that the Nile basin countries disregard political boundaries to coordinate and efficiently manage their water and land resources, as well as other resources, including labour and capital, so that water use externalities in the basin are internalized. That is, the water and other resources of the Nile basin countries are collectively managed and efficiently allocated by a basin planner, so much so that the current water resource dispute ceases to be a transboundary problem and becomes a mere domestic water resource allocation issue of an integrated Nile basin region where water allocation in the basin will be based solely on an economic efficiency criterion. The relevance of such a modeling approach lies in its capability to assess the significance of internalizing water use externalities in the basin in terms of absorbing the impacts of climate shocks.

The study applies a computable general equilibrium (CGE) modeling approach to evaluate the food security implications of internalizing Nile basin water use externalities under climate change. CGE models capture various inter-sectoral linkages as well as relevant economic feedbacks and determine relative product and factor prices endogenously via market-based interactions among economic agents. Providing an economy-wide perspective that captures the interaction between agriculture and other sectors, CGE models constitute an appropriate modeling approach to evaluate the economic and food security implications of climate change in the Nile basin.

In the literature, several CGE models are applied to assess the economic impact of climate change. Results from CGE models of Nile Basin countries show that climate change in Ethiopia reduces agricultural production and GDP (Gebreegziabher et al., 2015; Yalew et al., 2018; Robinson et al., 2011), increases income inequality (Mideksa, 2010), and affects the poor disproportionately (Robinson et al., 2011; Solomon et al., 2021). Similarly, CGE analysis reveals that climate change results in a reduced share of agriculture in GDP and decreased grain self-sufficiency in Egypt (Strzepek and Yates, 2000), reduced real GDP in Egypt (Elshennawy, et al., 2015), and decreased agricultural productivity in Tanzania (Bezabih et al., 2010). These studies apply a single-country CGE analysis and lack the transboundary perspective that characterizes the Nile River Basin. Besides, they don't distinguish between rainfed and irrigated agriculture, and fail to directly incorporate water as a separate factor of production.

Findings from multi-sector, multi-country CGE models reveal that climate change would reduce global food production, welfare, and GDP and raise food prices (Calzadilla et al., 2011; Calzadilla et al., 2013). Models applied to analyze adaptation strategies to climate change disclose that improved productivity yields better outcomes compared to an expansion in irrigated area in Sub-Saharan Africa and South Africa (Calzadilla et al., 2014). Few studies apply a multi-sector, multi-country CGE model to assess climate change impacts in the Nile Basin (Kahsay et al. 2017a; Kahsay et al. 2017b). The findings of these studies show that climate change is expected to reduce agricultural production and welfare and raise prices of crops in the Nile basin (Kahsay et al. 2017a), although in the short term, climate change improves water supply and irrigation water use, enhancing economic growth and welfare in the basin (Kahsay et al. 2017b). The results are mainly driven by climate change-induced changes in the availability, productivity, and allocation of land and water resources. Despite their transboundary perspective, these studies are limited to examining climate change impacts on agriculture and the broader economy, falling short of analyzing how climate change impacts translate into effects on food security. Besides, none of these studies address the implications of transboundary water use externalities in absorbing climate shocks.

The study presented here employs a modeling framework that couples a partial equilibrium and CGE model to evaluate the food security implications of internalizing Nile basin water use externalities under climate change. The CGE model applied in this study is based on the Global Trade Analysis Project (GTAP) model (Hertel, 1997). GTAP is a static-comparative, multi-region, multi-sector CGE model of the world economy that examines all aspects of an economy via its general equilibrium feature. The CGE model considered here is the version of the GTAP-W model (Calzadilla et al., 2010a) that distinguishes between rainfed and irrigated agriculture and introduces a new production structure that accounts for substitution possibilities between water and irrigated land in the production of irrigated agriculture. The GTAP-W model of the Nile basin region is integrated with the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), a partial equilibrium agricultural sector model that incorporates a water simulation model and crop yield response to climate change (Nelson et al., 2010).

Studies that investigate the pathways through which climate change impacts the state of food security in the Nile Basin and studies that consider modeling the basin as a single unit of analysis internalizing water use externalities, are as yet not reported. This study considers filling this gap. This study contributes to the existing literature in two major ways. First, it introduces a novel modeling approach that compares riparian– and basin-scale analysis of water resource management in the Nile basin under climate change. With the river basin recognized as the appropriate unit of analysis for water resource management (McKinney et al., 1999;, modeling the Nile Basin as a single unit of analysis, internalizing water use externalities in the basin would provide a new insight into water resource management options under climate change in the basin. The food security implications associated with internalizing water use externalities in the basin under climate change are evaluated relative to the case of the riparian-scale analysis.

Second, it advances the scope of the analysis from assessing economic impacts to evaluating food security implications of climate change in the Nile basin. The ‘food availability’ and ‘access to food’ dimensions of food security are considered to determine the pathways through which climate change impacts the state of food security in the basin.

Findings of the study provide pertinent information for devising appropriate climate change adaptation and mitigation mechanisms in the Nile basin. Besides, the study generates relevant information that facilitates informed and effective policy dialogue among the Nile riparian countries regarding the management and development of the scarce shared water resources of the basin in a sustainable manner. The study is also expected to shed light on the economic significance of cooperative management of the shared water resources of the Nile River Basin.

2. Modeling framework and data

2.1 Modeling framework

Climate change involves pervasive direct and indirect effects on various sectors of an economy so the analysis must incorporate inter-sectoral linkages and general equilibrium effects. CGE models that capture various inter-sectoral linkages and relevant economic feedbacks are therefore an appropriate modeling approach to evaluate climate change impacts. Price endogeneity and a general equilibrium perspective that captures all market-based interactions among economic agents constitute major features of CGE models that render them capable of examining the direct and indirect impacts of climate change.

However, despite their attractive attributes and widespread use as a tool for economy-wide analysis, CGE models as applied to water resource management issues are highly aggregated and lack the relevant details needed to assess the spatial allocation of water and land resources across crops at the agricultural plot level. Besides, CGE models are criticized as being insufficiently validated and often relying on parameters that are not econometrically estimated (Beckman et al., 2011). To remedy these limitations, this study applies a modeling framework that couples CGE and partial equilibrium models.

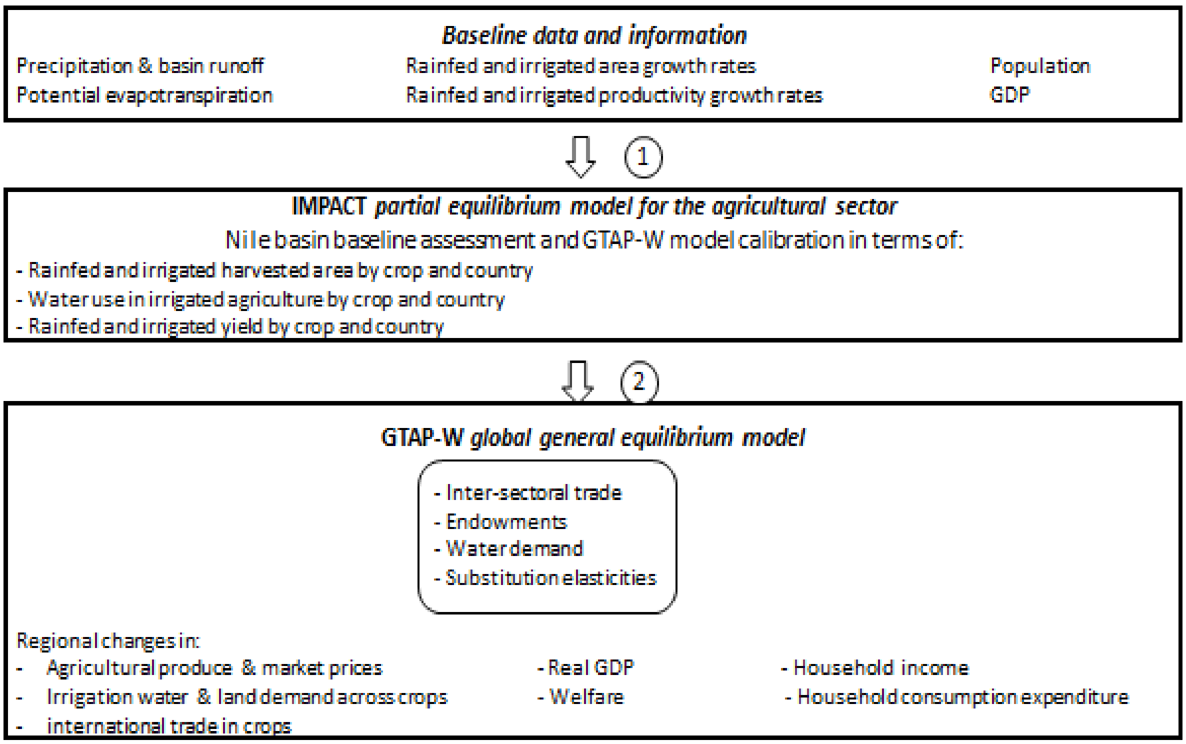
The CGE model applied in the study is based on the Global Trade Analysis Project GTAP) modeling framework (Hertel, 1997), developed at the Center for Global Trade Analysis, Purdue

University, USA. GTAP is a static comparative, multi-region, multi-sector CGE model of the world economy that examines all aspects of an economy through its general equilibrium feature. The study adopts the new version of the GTAP-W model (Calzadilla et al., 2010a) that distinguishes between rainfed and irrigated agriculture and implements water as a factor of production directly substitutable in the production process of irrigated agriculture (Calzadilla et al., 2010a). That is, irrigation water and irrigated land are substitutes in irrigated agricultural production. To incorporate water in the GTAP-W model, the agricultural land endowment in the GTAP database is disaggregated into rainfed land, irrigated land, and irrigation water following the procedure outlined in Calzadilla et al. (2011) and described below. Land used in livestock production is treated as pasture land.

The partial equilibrium model coupled to the GTAP-W model is the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model. The IMPACT model was developed at the International Food Policy Research Institute (IFPRI) in the early 1990s to support analysis of the challenges facing policymakers in feeding the world and sustainably reducing poverty (Rosegrant et al. 2008). The specification of the IMPACT model reflects the interdependence of countries and commodities in the global agricultural markets. Details of the IMPACT methodology are thoroughly documented in Rosegrant et al. (1995), Rosegrant et al. (2002), and Rosegrant et al. (2008). The IMPACT model has been updated and improved over time to provide researchers with a flexible tool to analyze evolving and more complex issues and better inform the choices decision makers face. This study uses results from the version of the IMPACT model developed by Nelson et al. (2010).

In linking the GTAP-W and IMPACT models, detailed data on land use and yield in irrigated and rainfed agriculture, as well as water use in irrigated production specified per country and crop, derived from the IMPACT model is used to calibrate and benchmark the baseline of the GTAP-W model (Figure 1). In a subsequent step, results from the IMPACT model that incorporates a water simulation model and crop yield response to climate change (Nelson et al., 2010) are used in designing the climate change scenario for the GTAP-W model. Detailed data on climate change-induced changes in irrigation water and rainfed and irrigated land for each country and crop generated by the IMPACT model are fed into the GTAP-W model to evaluate the economy-wide impacts of climate change in the Nile Basin.

Figure 1: Integrated IMPACT – GTAP-W modeling framework



Source: Kahsay et al. (2019)

2.2 Data

The core data of the model is the GTAP database. This is a global database describing bilateral trade patterns, production, consumption, and intermediate use of commodities and services. This study employs the GTAP 10 database that includes 141 regions and 65 sectors and describes the world economy for four reference years (2004, 2007, 2011 and 2014) (Aguiar et al, 2019). The latest reference year of the database (i.e., 2014) is used as a baseline for the study. The study is conducted at two scales of analysis: riparian – and basin-scale. Accordingly, two regional aggregation approaches, one based on political boundaries of the riparian countries and another that considers the basin boundary as a unit of analysis and combines all the riparian countries into a single region, are used in modeling the Nile basin countries. In the riparian approach, the 141 regions in the GTAP 10 database are aggregated into 7 regions: Egypt, Ethiopia, Sudan, Equatorial Lakes (EQL) region, rest of East Africa, the rest of Africa and the rest of the world (ROW) (See Appendix A). The EQL region comprises the four White Nile countries, Kenya, Rwanda, Tanzania, and Uganda, which are covered in the GTAP 10 database. The Nile Basing region comprises Egypt, Ethiopia, Sudan, and the EQL region. The regional aggregation highlights the significance of the Eastern Nile region in terms of the supply and the demand for Nile waters. In the GTAP 10 database, Sudan is aggregated into the rest of the Eastern Africa region. The SplitReg Program (Horridge 2011) is employed to split off Sudan from the composite region (rest of East Africa). The basin-scale modeling approach combines all the Nile basin countries into a single region. Regional aggregation for the basin-scale approach, where all the Nile basin countries are aggregated into a single region, is shown in Appendix B.

The 65 sectors in the GTAP 10 database are aggregated for this study into 20 sectors, of which 8 are agricultural sectors and 12 nonagricultural sectors (see Appendix C). Since climate change directly impacts crops, the analysis in this study zooms in on the seven crop sectors. The GTAP 10 database also provides data on five factors of production (endowments), namely land, skilled labour, unskilled labour, capital, and natural resources. For this study, the land endowment is disaggregated into rainfed land, irrigated land, and irrigation water. Land used for animal production is treated as pasture land. Therefore, the number of endowments in this study is expanded from five to eight using the method outlined in Calcadilla et al. (2011). The relative share of rainfed and irrigated production in total production is used to split the land rent in the GTAP database into a value for rainfed land and a value for irrigated land – water composite for each crop in each region. In thea next step, the ratio of irrigated yield to rainfed yield is used to split the value of irrigated land – water composite into the value of irrigated land and the value of irrigation water. This process results in the GTAP-W model of the Nile Basin.

3 Scenario design

The study considers two scenarios: the baseline and climate change scenarios.

3.1 Baseline scenario

The baseline scenario projects the GTAP 10 database from 2014 to 2050 to develop a future baseline assuming no climate change. The future benchmark equilibrium dataset for the GTAP-W model is derived using the method proposed by Dixon and Rimmer (2002). Projected cumulative growth rates in macroeconomic variables, as well as land and water use in the world economy, are used to construct a future benchmark equilibrium. Projection of rainfed and irrigated land use and irrigation water endowment across regions is based on the IMPACT data[1] (Nelson et al., 2010). Nelson et al. (2010) provide detailed baseline data for the year 2000 and simulation data until the year 2050 with respect to irrigation water use, crop yields, and cropped area, distinguishing between 20 rainfed and irrigated crops and 281 food processing units (FPU) for 115 economies in 126 river basins, including all the Nile basin countries considered in this study. Table 1 shows the cumulative growth rates used to project the world economy towards the year 2050.

Table 1: Percent change in core variables in 2050 compared to the baseline year 2014 by region under no climate change condition

	Irrigation water[1]	Irrigated land[1]	Rainfed land[1]	Population[1]	GDP[2]	Skilled Labour[3]	Unskilled labour[3]	Capital[3]	Pasture land[3]	Natural resource[3]
Egypt	1.58	15.84	0.0*	49.2	536.0	137.35	105.95	156.93	11.89	289.88
Ethiopia	28.46	65.42	36.52	81.4	591.3	153.37	120.56	136.87	120.41	62
Sudan	8.44	211.73	37.33	63.6	361.4	84.91	83.54	89.64	47.61	164.99
Rest of	0.07	37.11	34.14	85.0	276.9	57.33	55.92	60.16	34.65	107.06

[1] Changes in agricultural area in the IMPACT model has exogenous and endogenous component. The exogenous component reflects a combination of historical trends and assessments about future Changes, including urbanization and other land use change while the endogenous one is a price-responsive component (Nelson et al., 2010).

East Africa										
EQL Region	66.4	89.3	33.6	96.6	918.8	260.04	216.81	268.53	145.6	528.4
Rest of Africa	39.28	55.09	24.98	70.3	389.6	112.21	83.37	111.24	30.65	148.28
ROW	19.42	72.12	-2.68	23.1	155.7	18.18	17.2	18.66	5.8	22.46
Nile Basin	5.6	131.2	31.4	81.2	615.5	156.21	124.15	167.94	48.59	366.82

Source: [1]Own computation based on data from Nelson et al. (2010)

[2]Own computation based on data from Foure et al. (2012)

[3]Based on macro projection simulation results

[*]Rain-fed agriculture hardly exists in Egypt

Note: Irrigation water and irrigated land refer to water used in irrigated agriculture and land under irrigation, respectively

3.2 Climate change scenario

The food security implication of climate change in the Nile Basin is assessed for one global emissions scenario (B1) from two global circulation models (GCM) (CSIRO[2] and MIROC[3]) in 2050. The average of CSIRO and MIROC data is considered in determining the climate change effect for the B1 scenario. The B1 scenario describes a future with high population growth but rapid change in economic structure towards a service and information economy, reduction in material intensity, and use of clean and efficient technologies (IPCC, 2000). Climate change-related changes in irrigated land, rainfed land, and irrigation water endowment required to implement climate change shocks are based on the IMPACT data (Nelson et al., 2010) (Table 2). Climate change impact on irrigated and rainfed yield is derived from data on climate change

[2] CSIRO Commonwealth Scientific and Industrial Research Organization; abbreviation for the CSIRO-Mk3.0 general circulation model (Nelson et al., 2010)

[3] MIROC abbreviation for the MIROC 3.2 medium resolution general circulation model (produced by the Center for Climate System Research, University of Tokyo; the National Institute for Environmental Studies; and the Frontier Research Center for Global Change, Japan) (Nelson et al., 2010)

impact on temperature and precipitation in the Nile basin from Beyen et al. (2010) and crop yield responses to changes in precipitation and temperature by crop from Calzadilla et al. (2010b).

Beyene et al. (2010) predict the impact of climate change on key climate variables, including temperature and precipitation, using 11 general circulation models (GCMs). According to Beyene et al. (2010), the average rise in temperature in Lake Victoria, the Blue Nile, and the entire Nile for the 30-years centered around the period 2040–2069 is estimated at 1.9, 2.55, and 2.76 percent, respectively, under the B1 scenario. During the same period, precipitation in Lake Victoria, the Blue Nile, and the entire Nile is expected to increase by 4.7, 3.6, and 3.1 percent, respectively, under the B1 scenario (Beyene et al., 2010). Climate change shocks related to irrigated and rainfed yield as well as crop water requirement, implemented in the riparian and basin scale models, are shown in Table 3. Heat impact on labour productivity and a variation in agricultural multi-factor productivity are based on data from Roson and Sartori (2016) and Beyene et al. (2010) (Tables 4 and 5). All the climate shocks implemented in the study are scaled by the percent of the population living in the basin area in both the riparian and basin scale analysis in order to isolate the effect of climate change on the Nile basin part of the Nile Basin countries.

Table 2: Percent change in land and water endowments in the Nile basin due to climate change B1 scenario in 2050

	No climate change			Climate change B1 scenario			% change*		
	Irrigated land	Rainfed land	Irrigation water	Irrigated land	Rainfed land	Irrigation water	Irrigated land	Rainfed land	Irrigation water
Egypt	4800.6	0.0	29.6	4235.4	0.0	29.2	-10.8	0.0	-1.2
Ethiopia	399.2	17401.8	1.5	274.9	17281.9	1.3	-11.8	-0.3	-4.3
Sudan	1062.9	19654.1	8.5	1184.7	18575.2	8.3	10.1	-4.8	-2.1
EQL Region	607.1	29584.7	2.1	635.5	29164.7	2.0	2.3	-0.7	-1.7
Basin total	6869.8	66640.6	41.6	6330.5	65021.8	40.8	-4.8	-1.5	-1.2

Source: Own computation based on data from Nelson et al. (2010)
*Percent changes are adjusted for the share of the population in each country living within the Nile base part
Note: Irrigation water and irrigated land refer to water used in irrigated agriculture and land under irrigation, respectively

Table 3: Change in crop water requirement and yield response to climate change in the Nile basin due to the climate change B1 scenario in 2050

	Change in crop water requirement (%)[1]					Yield response to climate change (%)[2]				
	Egypt	Ethiopia	Sudan	EQL Region	Basin Total	Egypt	Ethiopia	Sudan	EQL Region	Basin Total
Rice	1.93	0.53	1.27	5.6	1.62	-16.192	-5.6	-14.4	-5.2	-10.0
Wheat	1.66	1.10	0.51	0.9	1.02	-16.192	-5.6	-14.4	-5.2	-10.0
Cereals	1.52	2.79	6.42	1.6	4.45	-12.236	-5.9	-14.8	-5.6	-10.3
Other crops	1.54	3.14	0.42	0.8	0.92	-16.192	-5.6	-14.4	-5.2	-10.0
Vegetables & fruits	1.49	3.88	0.20	-0.7	0.95	-16.192	-5.6	-14.4	-5.2	-10.0
Oilseeds	1.60	4.00	0.47	-2.4	-2.92	-16.192	-5.6	-14.4	-5.2	-10.0
Sugar crops	3.04	2.48	1.19	3.6	1.62	-12.236	-5.9	-14.8	-5.6	-10.3

Source: [1]Own computation based on data from Nelson et al. (2010)
[2]Own computation based on data from Nelson et al. (2010), Beyene et al. (2010), and Calzadilla et al. (2010b)

Table 4: Percent change in labour productivity in the Nile basin due to climate change B1 scenario in 2050

	Rice	Wheat	Cereals	Other crops	Vegetables & fruits	Oilseeds	Sugar crops	Livestock and livestock products	Processed food	Extraction	Electricity	Manufacturing	Construction
Egypt	-6.43	-6.43	-6.43	-6.43	-6.43	-6.43	-6.43	-6.43	-1.42	-6.43	0	-1.42	-1.42
Ethiopia	0	0	0	0	0	0	0	0	0	0	0	0	0
Sudan	-3.08	-3.08	-3.08	-3.08	-3.08	-3.08	-3.08	-3.08	0	-3.08	0	-0.68	-0.68
EQL region	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	0	0	0	0	0	0
Basin total	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	0.0	-0.1	-1.1	0.0	-0.1	-0.1

Source: Own computation based on data from Roson and Sartori (2016) and Beyene et al. (2010)

Table 5: Percent change in multi-factor productivity in the Nile basin due to climate change B1 scenario in 2050

	Rice	Wheat	Cereals	Other crops	Vegetables and fruits	Oilseeds	Sugar crops
Egypt	-2.44	-10.33	-5.47	-6.38	-6.38	-6.38	-5.47
Ethiopia	-1.35	-6.49	-3.29	-3.92	-3.92	-3.92	-3.29
Sudan	-2.73	-12.46	-6.42	-7.59	-7.59	-7.59	-6.42
EQL region	-1.9	-9.6	-4.8	-5.8	-5.8	-5.8	-4.8
Basin total	-1.4	-2.9	-3.8	-2.2	-2.2	-2.2	-3.8

Source: Own computation based on data from Roson and Sartori (2016) and Beyene et al. (2010)

4 Simulation results

The food security outcomes of internalizing water use externalities in the Nile basin under climate change in 2050 are assessed using the 'food availability' and 'access to food' dimensions of food security. Impacts on crop production and import – export trade in crops are used to assess the effect on the 'food availability' dimension of food security. The 'access to food' dimension of food security is evaluated through effects on crop prices and real returns to primary factors. Effects are evaluated relative to the projected 2050 benchmark equilibrium that assumes no climate change. The significance of basin-scale analysis with water use externalities internalized in absorbing climate shocks in the basin is assessed relative to the results of the riparian-scale analysis.

Climate change primarily affects the availability and use of vital agricultural resources such as irrigation water, irrigated land, and rainfed land. The impact of climate change in 2050 on these indispensable agricultural resources is reported in Table 6. Results for the riparian-scale analysis indicate that climate change results in a decline in irrigation water demand[4] for most crops. The demand for irrigation water in the basin for all crops combined rises by 4.4 percent, which translates to 1.85 Km^3 (Table 6). With the Nile waters already heavily utilized and almost fully allocated, the results reveal a basin-wide deficit of 1.85 Km^3 in irrigation water due to climate change.

[4] A decline in the demand for irrigation water in a particular crop implies a decrease in water allocation to that crop and vice versa.

Results for climate change impacts on irrigated land show a pattern similar to that of irrigation water due to the complementarity of the two resources. The demand for irrigated land falls for all crops except other crops and oilseeds, resulting in a 60.7 thousand hectares (0.9 %) decline in total basin-wide demand for irrigated land (Table 6). The demand for rainfed land tends to increase for most crops, resulting in an 842 thousand hectares (1.4%) increase in basin-wide demand for rainfed land (Table 6). When water use externality in the basin is internalized via a basin-scale modeling, the total basin-wide demand for irrigation water falls by 1.9 percent, which amounts to 0.8 Km^3 (Table 6), indicating the significance of coordinated basin-wide management of the Nile waters in easing the severe water scarcity exacerbated by climate change in the basin. Following the decline in the demand for irrigation water, the overall basin-wide demand for irrigated land falls by 432.1 thousand hectares (6.3%) (Table 6). Similarly, the basin-wide demand for rainfed land declines by 1684.6 thousand hectares (2.7%) due to climate change under the basin-scale analysis (Table 6). About 2.7 km^3 of irrigation water is saved under the basin-scale modeling compared to that under the riparian-scale analysis, indicating the significance of internalizing water use externality in easing the pressure on the already scarce water resources of the basin. The gain in irrigated land and rainfed land resources is in the order of 371 thousand and 2.5 million hectares, respectively, testifying to the immense significance of coordinated basin-scale management of the basin's land and water resources.

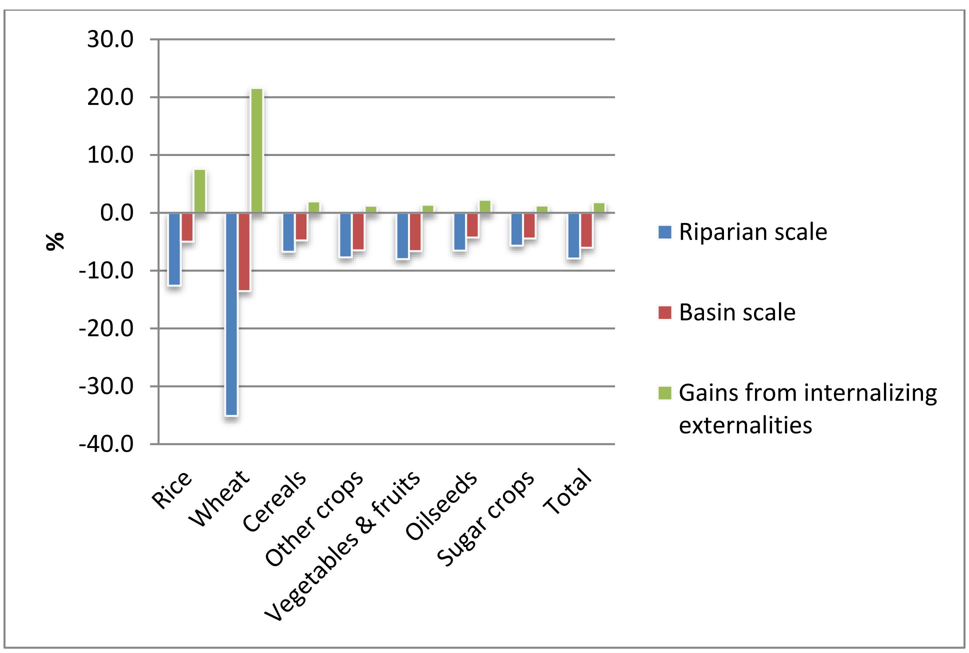
Table 6: Change in demand for irrigation water, irrigated land and rainfed land in 2050 due to climate change compared to the predicted baseline scenario: Riparian and basin scale results

	Riparian scale (% change)			Basin scale (% change)			Riparian scale (Total change)			Basin scale (Total change)		
	Irrigation water	Irrigated land	Rainfed land	Irrigation water	Irrigated land	Rainfed land	Irrigation water (Km^3)	Irrigated land (‘000 ha)	Rainfed land (‘000 ha)	Irrigation water (Km^3)	Irrigated land (‘000 ha)	Rainfed land (‘000 ha)
Rice	-1.2	-8.2	-7.6	-0.5	-5.0	-0.9	-0.05	-33.5	-26.3	-0.02	-20.2	-3.1
Wheat	-24.3	-27.0	-10.9	-8.7	-12.3	-8.7	-1.22	-197.4	-272.6	-0.44	-90.2	-217.4
Cereals	-0.7	-5.8	6.9	3.2	-3.6	1.0	-0.05	-52.3	1638.3	0.20	-32.8	244.6
Other crops	46.3	33.8	-2.5	-2.7	-6.5	-5.9	5.01	686.6	-662.5	-0.29	-131.9	-1570.2
Vegetables & fruits	-16.0	-18.4	0.3	-2.1	-5.9	-2.1	-1.85	-466.0	17.1	-0.24	-150.3	-130.1
Oil seeds	-1.4	3.7	7.0	-3.1	-3.8	-0.9	-0.02	2.1	123.8	-0.05	-2.1	-15.7
Sugar crops	2.8	-3.5	6.3	2.1	-2.2	1.9	0.04	-7.3	24.1	0.03	-4.6	7.2
Total	4.4	-0.9	1.4	-1.9	-6.3	-2.7	1.85	-60.7	842.0	-0.80	-432.1	-1684.6

Note: Irrigation water and irrigated land refer to water used in irrigated agriculture and land under irrigation, respectively

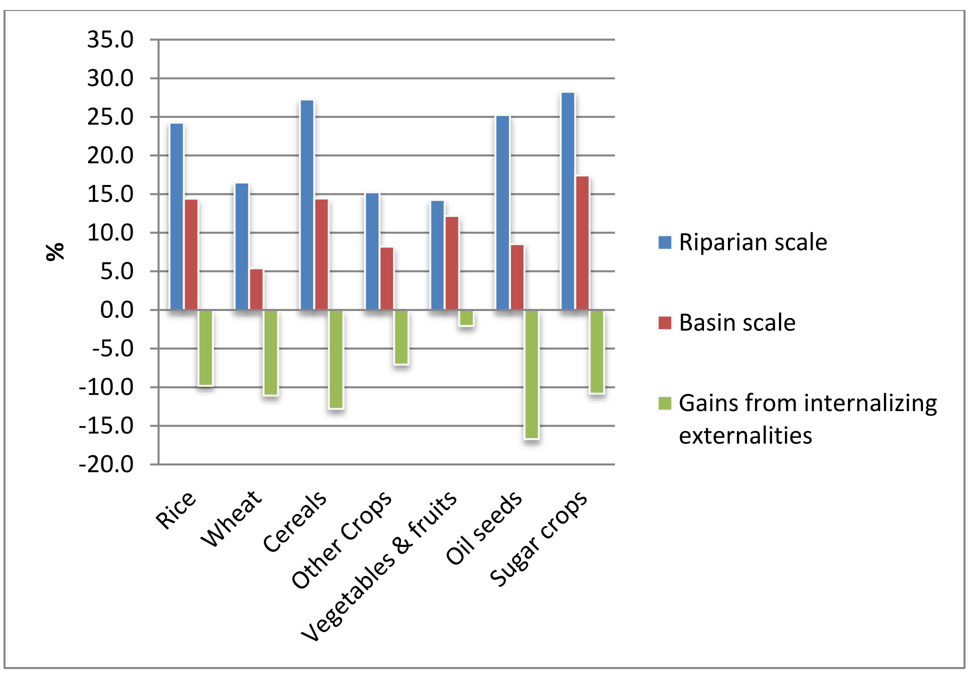
Climate change impacts on water and land resources are inevitably reflected in crop production. The simulation results for the riparian-scale model reveal that climate change results in a substantial decline in production for all crops, translating to a 7.9 percent decline for all crops combined (Figure 2) that amounts to 30.9 million tons. Under the basin-scale analysis, climate change still induces a decline in the production of all crops, resulting in a 6.1 percent fall in output for all crops combined (Figure 2) that translates to a 23.7 million tons decline in production. The gains in crop output in the basin-scale analysis relative to that in the riparian-scale analysis range from 1.2 percent in the cereals sector to 21.6 percent in the wheat sector (Figure 2). The basin-wide gain in production for all crops combined amounts to 7.2 million tons, indicating the significance of internalizing water use externalities in the basin in stimulating crop production. The substantial loss in food production due to climate change inevitably results in reduced food availability and hence deterioration in the state of food security in the basin. In this regard, the role of internalizing water use externality in lessening the adverse food security outcomes of climate change is quite significant.

Figure 2: Percent change in crop production in 2050 due to climate change compared to the predicted baseline scenario in the riparian and basin scale assessment



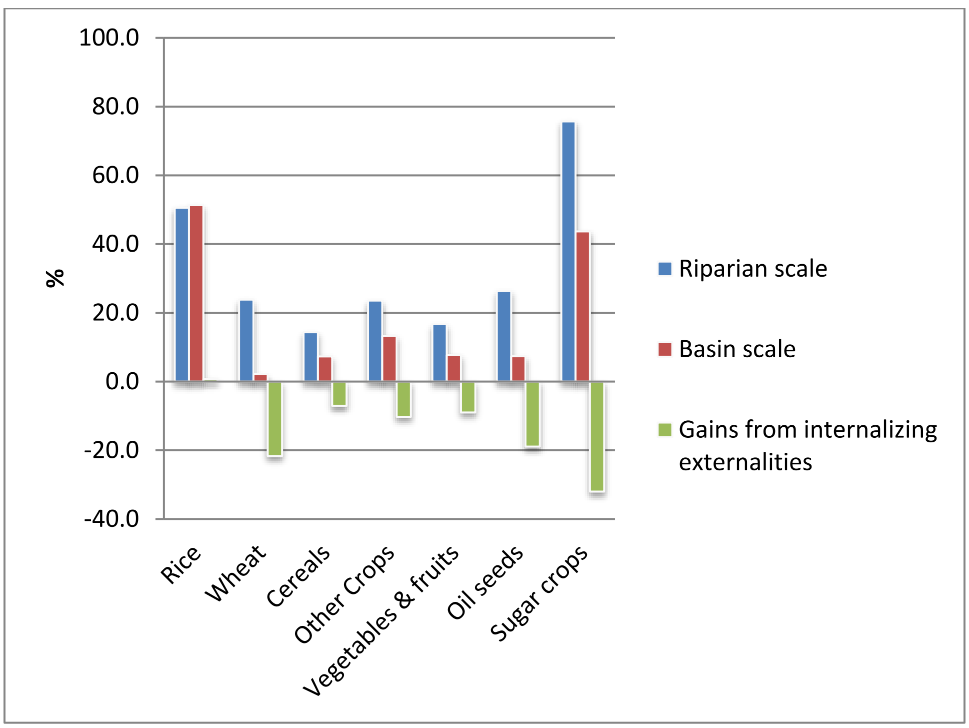
The market responds to changes in production through adjustments in market prices. Decline in crop supply due to reduced crop production caused by climate change necessarily results in increased market prices of crops. Figure 3 exhibits changes in market prices of crops induced by climate change under the riparian- and basin-scale analysis, and the difference in the results for the two scales of analysis. Under the riparian-scale analysis, prices surge significantly for all crops (Figure 3) due to climate-change-induced reduction in crop output. As a matter of course, the substantial rise in crop prices adversely affects the 'access to food' dimension of food security and hence necessarily worsens the food insecurity situation in the basin. When water use externality is internalized through basin-scale water management, the market price of crops still rises, but to a substantially lesser extent compared to the case of the riparian-scale analysis (Figure 3). Thus, basin-wide management of the water and land resources of the Nile basin significantly reduces the adverse impact of climate change on crop prices and hence the access to food and the state of food security in the basin.

Figure 3: Percentage change in market prices of crop in 2050 due to climate change compared to the predicted baseline scenario in the riparian and basin scale assessment



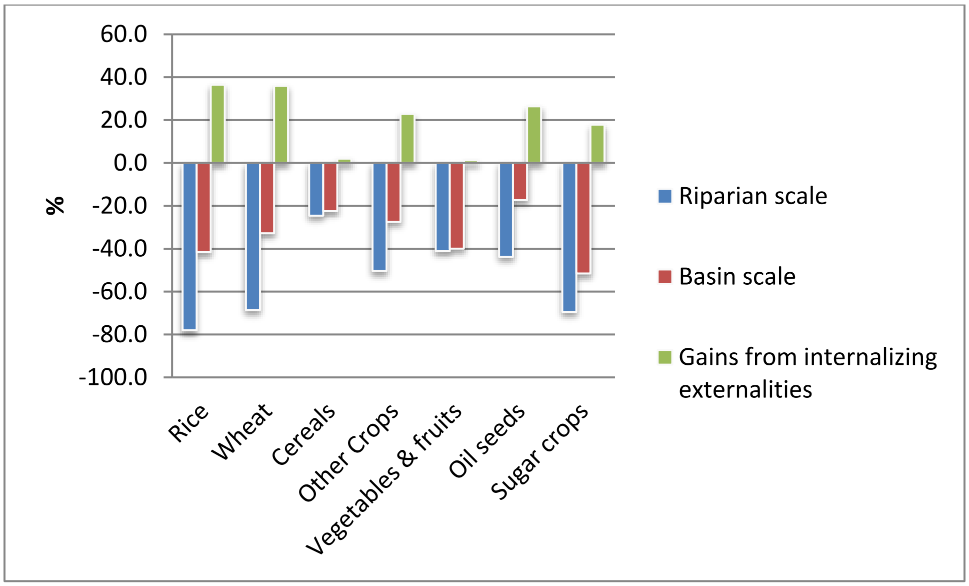
The deficit in domestic crop supply induced by the decline in crop production caused by climate change is expected to be balanced through adjustments in trade flows in crops. Imports rise substantially for all crops under both the riparian- and basin-scale analysis (Figure 4). However, the rise in crop imports under the basin-scale analysis is less prominent since the climate change impact on crop production and hence the deficit in domestic crop supply in the basin is relatively lower under this scale of analysis. The gains in terms of lower import demand for crops when water use externalities are internalized through basin-scale modeling range from 0.7 to 21.6 percent (Figure 4), resulting in substantial savings of foreign exchange required to pay for crop imports.

Figure 4: Percentage change in crop imports in 2050 due to climate change compared to the predicted baseline scenario in the riparian and basin scale assessment



In addition to the rise in crop imports, crop exports decline significantly under both scales of analysis to bridge the deficit in domestic crop supply caused by climate change (Figure 5). Decline in crop exports is relatively lower under the basin-scale analysis compared to that under the riparian-scale analysis since the climate change-induced deficit in domestic crop supply is lower in the basin-scale analysis. This signifies the contribution of basin-wide management of the Nile basin resources in saving foreign exchange earnings that could be lost from reduced crop exports in the basin. The rise in crop imports coupled with the decline in crop exports improves the food security situation in the basin through its positive effect on the "food availability' dimension of food security. This benefit is more prominent in the basin-scale management of water resources compared to the riparian-scale water management.

Figure 5: Percentage change in crop exports in 2050 due to climate change compared to the predicted baseline scenario in the riparian and basin scale assessment



Climate change also depresses the real return to primary factors that measure the changes in return to factors relative to the price index of consumption expenditure. Under the riparian-scale analysis, real return to unskilled labour, skilled labour, and capital fall by 7.3, 7, and 7.3 percent, respectively, due to climate change. Real return to unskilled labor (the least paid segment of the working population) is particularly important as it indicates trends in poverty. Standing at 3.9, 3.8, and 3.8 percent, respectively, for unskilled labour, skilled labour, and capital, climate change impacts on real return to primary factors for the basin-scale analysis are only about half of that for the riparian-scale analysis. Apparently, basin-wide management of the water and land resources of the Nile basin provides better capacity to absorb the income effect and hence poverty implications of climate change compared to the riparian-scale water management.

5 Discussion and conclusion

A multi-region, multi-sector computable general equilibrium (CGE) modeling framework that incorporates water as a factor of production in irrigated agriculture is used to assess the food security implications of internalizing water use externality in the Nile basin under climate change. The effect of one exogenous climate change scenario (B1 scenario) is considered for analysis using two modeling approaches, namely riparian- and basin-scale modeling. Food security implications of climate change are evaluated based on the 'food availability' and 'access to food' dimensions of food security.

The results of the study reveal significant adverse effects of climate change on food security in the Nile basin under both scales of analysis. Crop production declines substantially due to climate change, resulting in a surge in market prices of crops. Crop imports increase while crop exports decline to bridge the deficit in crop supply caused by climate change-induced decline in crop production, indicating the significant role trade can potentially play as an adaptation mechanism to climate change in the Basin. Moreover, climate change causes a significant adverse effect on real return to the primary factors labour (skilled and unskilled) and capital. The consequences of climate change on food security are apparent. The substantial decline in crop production due to climate change reduces food availability, thereby aggravating the food security situation in the basin. The surge in crop prices, coupled with the decline in real return to primary factors, curtails access to food, thereby adversely affecting the state of food security in the basin. Climate change thus inflicts significant adverse effects on food security in the Nile basin through its adverse impact on the 'food availability' and 'access to food' dimensions of food security.

The results unequivocally disclose that the adverse effects of climate change on food security in the Nile Basin are substantially lower in the basin-scale analysis compared to those in the riparian-scale analysis. Cooperative management of the water and land resources of the Nile basin countries helps internalize the water use externalities in the basin and results in efficient allocation of the basin's productive resources, thereby offering significant capacity to absorb the production and price shocks instigated by climate change. Internalizing water use externality significantly eases climate-change-induced pressure on water and land resources of the basin, and substantially diminishes the adverse impact of climate change on crop production and crop prices. Besides, internalizing water use externality depresses the adverse income effect and hence poverty implications of climate change and downscales the impact of climate change on food security in the basin.

Compared to previous studies, this study represents the first effort to use a global CGE model to analyze the food security implications of internalizing water use externalities in the Nile basin under climate change. The static nature of the GTAP-W model constitutes a limitation of the study. A dynamic model is theoretically expected to be able to better absorb climate change shocks in the basin through adjustments in capital stocks, such as investments in irrigation infrastructure. However, despite the static nature of the model, the results of the current analysis demonstrate the potential risk climate change poses on food security in the basin and the role cooperative basin-wide management of the Nile basin resource can play in absorbing climate shocks.

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Appendix A: GTAP regions aggregation _Riparian Scale

Region	**Comprising**
Egypt	Egypt.
Ethiopia	Ethiopia.
Sudan	Sudan
EQL Region	Kenya; Rwanda; Tanzania; Uganda.
Rest of East Africa	Burundi, Comoros, Djibouti, Eritrea, Mayotte, Seychelles, Somalia
Rest of Africa	Morocco; Tunisia; Rest of North Africa; Benin; Burkina Faso; Cameroon; Cote d'Ivoire; Ghana; Guinea; Nigeria; Senegal; Togo; Rest of Western Africa; Central Africa; South Central Africa; Madagascar; Malawi; Mauritius; Mozambique; Zambia; Zimbabwe; Botswana; Namibia; South Africa; Rest of South African Customs .
Rest of the World	Australia; New Zealand; Rest of Oceania; China; Hong Kong; Japan; Korea; Mongolia; Taiwan; Rest of East Asia; Brunei Darussalam; Cambodia; Indonesia; Lao People's Democratic Republic; Malaysia; Philippines; Singapore; Thailand; Viet Nam; Rest of Southeast Asia;

	Bangladesh; India; Nepal; Pakistan; Sri Lanka; Rest of South Asia; Canada; United States of America; Mexico; Rest of North America; Argentina; Bolivia; Brazil; Chile; Colombia; Ecuador; Paraguay; Peru; Uruguay; Venezuela; Rest of South America; Costa Rica; Guatemala; Honduras; Nicaragua; Panama; El Salvador; Rest of Central America; Dominican Republic; Jamaica; Puerto Rico; Trinidad and Tobago; Caribbean; Austria; Belgium; Bulgaria; Croatia; Cyprus; Czech Republic; Denmark; Estonia; Finland; France; Germany; Greece; Hungary; Ireland; Italy; Latvia; Lithuania; Luxembourg; Malta; Netherlands; Poland; Portugal; Romania; Slovakia; Slovenia; Spain; Sweden; United Kingdom; Switzerland; Norway; Rest of EFTA; Albania; Belarus; Russian Federation; Ukraine; Rest of Eastern Europe; Rest of Europe; Kazakhstan; Kyrgyzstan; Tajikistan; Rest of Former Soviet Union; Armenia; Azerbaijan; Georgia; Bahrain; Iran Islamic Republic of; Israel; Jordan; Kuwait; Oman; Qatar; Saudi Arabia; Turkey; United Arab Emirates; Rest of Western Asia; Rest of the World.

Appendix B: GTAP regions aggregation _Basin Scale

Region	Comprising
Nile Basin	Egypt; Ethiopia; Kenya; Rwanda; Tanzania; Uganda
Rest of East Africa	Burundi, Comoros, Djibouti, Eritrea, Mayotte, Seychelles, Somalia
Rest of Africa	Morocco; Tunisia; Rest of North Africa; Benin; Burkina Faso; Cameroon; Cote d'Ivoire; Ghana; Guinea; Nigeria; Senegal; Togo; Rest of Western Africa; Central Africa; South Central Africa; Madagascar; Malawi; Mauritius; Mozambique; Zambia; Zimbabwe; Botswana; Namibia; South Africa; Rest of South African Customs .
Rest of the World	Australia; New Zealand; Rest of Oceania; China; Hong Kong; Japan; Korea; Mongolia; Taiwan; Rest of East Asia; Brunei Darussalam; Cambodia; Indonesia; Lao People's Democratic Republ; Malaysia; Philippines; Singapore; Thailand; Viet Nam; Rest of Southeast Asia; Bangladesh; India; Nepal; Pakistan; Sri Lanka; Rest of South Asia; Canada; United States of America; Mexico; Rest of North America; Argentina; Bolivia; Brazil; Chile; Colombia; Ecuador; Paraguay; Peru; Uruguay; Venezuela; Rest of South America; Costa Rica; Guatemala; Honduras;

	Nicaragua; Panama; El Salvador; Rest of Central America; Dominican Republic; Jamaica; Puerto Rico; Trinidad and Tobago; Caribbean; Austria; Belgium; Bulgaria; Croatia; Cyprus; Czech Republic; Denmark; Estonia; Finland; France; Germany; Greece; Hungary; Ireland; Italy; Latvia; Lithuania; Luxembourg; Malta; Netherlands; Poland; Portugal; Romania; Slovakia; Slovenia; Spain; Sweden; United Kingdom; Switzerland; Norway; Rest of EFTA; Albania; Belarus; Russian Federation; Ukraine; Rest of Eastern Europe; Rest of Europe; Kazakhstan; Kyrgyzstan; Tajikistan; Rest of Former Soviet Union; Armenia; Azerbaijan; Georgia; Bahrain; Iran Islamic Republic of; Israel; Jordan; Kuwait; Oman; Qatar; Saudi Arabia; Turkey; United Arab Emirates; Rest of Western Asia; Rest of the World.

Appendix C. GTAP Sectors aggregation

Sector	**Comprising**
Rice	Paddy rice.
Wheat	Wheat.
Cereals	Cereal grains nec.
Other Crops	Plant-based fibers; Crops nec.
Vegetables and fruits	Vegetables, fruit, nuts.
Oilseeds	Oil seeds.
Sugar Crops	Sugar cane, sugar beet.
Livestock and livestock products	Bovine cattle, sheep and goats; Animal products nec; Raw milk; Wool, silk-worm cocoons; Bovine meat products; Meat products nec.
Processed food	Vegetable oils and fats; Dairy products; Processed rice; Sugar; Food products nec; Beverages and tobacco products.
Extraction	Forestry; Fishing.
Coal	Coal.
crude	Oil.
Gas distribution	Gas; Gas manufacture, distribution.
Petro	Petroleum, coal products.
Electricity	Electricity.
Manufacturing	Textiles; Wearing apparel; Leather products; Wood products; Paper products, publishing; Chemical products; Basic pharmaceutical products; Rubber and plastic products; Ferrous metals; Metals nec; Metal products; Computer, electronic and

	optic; Electrical equipment; Machinery and equipment nec; Motor vehicles and parts; Transport equipment nec; Manufactures nec.
Construction	Construction.
Mining	Minerals nec; Mineral products nec.
Water	Water distribution.
Services	Trade; Accommodation, Food and servic; Transport nec; Water transport; Air transport; Warehousing and support activi; Communication; Financial services nec; Insurance; Real estate activities; Business services nec; Recreational and other service; Public Administration and defe; Education; Human health and social work a; Dwellings.

Note: nec – not elsewhere counted.

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