Water Use and Agricultural Productivity Growth in Sub-Saharan Africa

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Abstract

Today, we are confronted with one of the greatest challenges of the 21st century: meeting the increasing needs of the population while reducing the damage caused by agriculture to the natural resources, namely water and land. Water is a complex resource, unlike a stable resource over human lifetime, such as land. To date, the empirical literature on the estimation of productivity in agriculture has disregarded water as an input. Given that it constitutes a necessary input, then its efficient use becomes a prerequisite condition. The main objective of this study was to investigate productivity growth in agriculture in sub-Saharan Africa, taking into account water as an input. The true-random Stochastic Production Frontier (SPF) was used to estimate the agricultural production function incorporating water as an input and to derive the total factor productivity (TFP) using a sample of 19 countries for the period 1991–2014. The results of the SFA model showed that the classical coefficients of the production function, including water endowment as an input, have a significant and positive impact on agricultural production growth after correction for the potential endogeneity bias. The average growth rate of TFP taking into account water as an input was estimated at 0.045% per year for the full sample period, a figure considerably lower than classical TFP estimated at an average rate of 1% per year. For the period 1991–2001, the rate was negative and estimated at -0.44% and 0.36% for the period 2002–2012. The higher performance in 2002–2012 may be due to the significant adoption of good agricultural practices along with technological advances that allowed for saving water (between -0.08% and -0.05% on average per year). Therefore it would be advisable to focus more on good practices in water saving, which are key to efficient use of water in agriculture.

Key words: agricultural productivity, water endowment, Malmquist index, SPF, SSA

1. Introduction

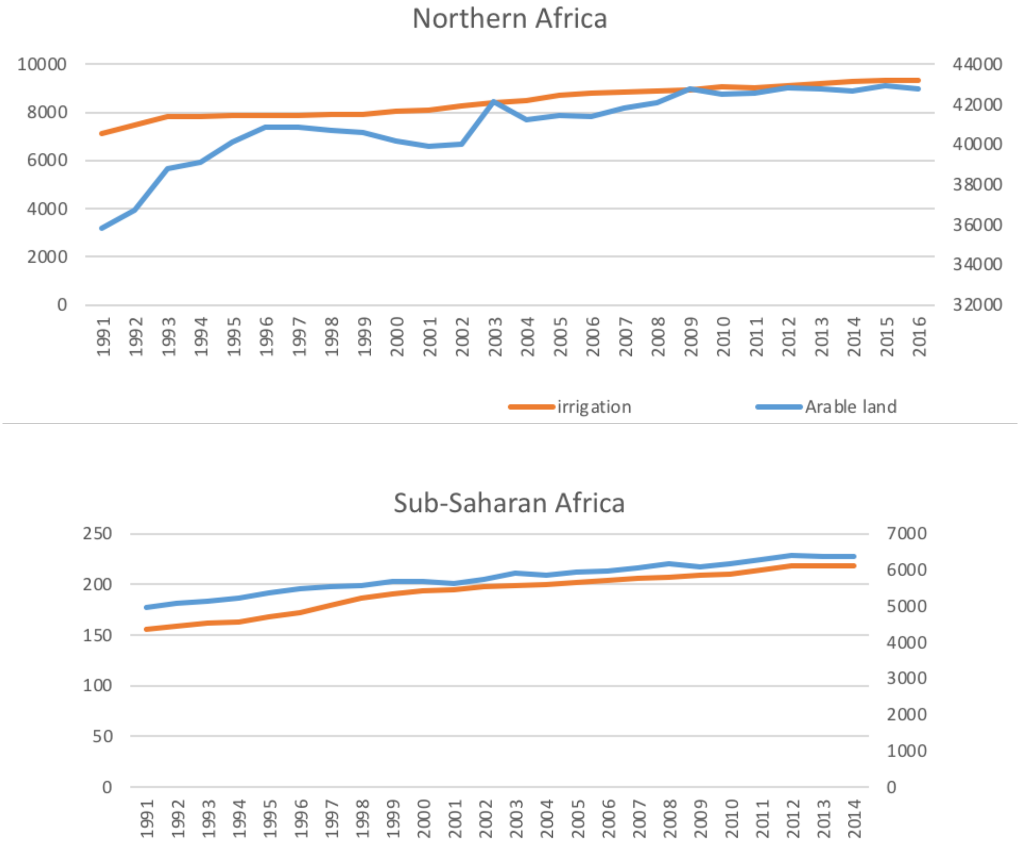
In future, sub-Saharan Africa will have to contend with one of the greatest challenges of the 21st century: meeting the increasing food needs of the population while reducing the damage caused to natural resources (i.e., water and land) by agriculture. The continent faces several challenges, among which the most important are: persistence of pollution, environment degradation and climate change. The green growth model offers a way that allows agriculture to be more resilient to the effects of climate change and population growth. The world demand for natural resources increased by 240% between 1961 and 2008 and, at the same time, deforestation and bad agricultural practices represented 65% of carbon emission in Africa (BAD and WWF, 2012). According to the sixth assessment report of the Intergovernmental Experts Group on Climate Change (IEGCC) published in 2021, the African continent, which is the lowest contributor to climate degradation, is among the regions in the world that are most vulnerable to climate change, causing uncertainties about the availability of water (Masson-Delmotte et al, 2021). Water is an essential input in agricultural production and hence plays an important role in food security. According to 'The State of Food and Agriculture (SOFA)' report(FAO, 2020), available freshwater resources have decreased by 20% during the two last decades (1997-2017), underlining the importance to produce more with less water, especially in the agriculture sector, which uses significant quantities of available water (70% of all water withdrawals globally). The "zero hunger" objective of sustainable development cannot be achieved without careful use of water in the food production process. The SOFA Report (FAO, 2020) stresses the importance of a more productive and sustainable use of freshwater and rainfall water in the agriculture sector to achieve that objective. This study considered water endowment of each region as an input factor in the agricultural production function. What then would the agricultural productivity growth be when water is integrated in the production function? And what is the difference compared with traditional measurement of productivity?

During the last 20 years, water use increased considerably as a consequence of population expansion and irrigated agriculture. The use of freshwater by agriculture accounts for 70% of all freshwater withdrawals globally. In Africa, water use by agriculture increased by 90%, on average. In the Sahel countries in particular, the use of water for agricultural purposes accounts for 93% of the available quantities of freshwater (Wrathall, 2018).

The water used for agricultural purposes comes mainly from rainfall, surface water sources and underground water. Rainfed agriculture, that is non-irrigated agriculture, depends entirely on rainfall water stored in the soil. This kind of agriculture is only possible in regions where the distribution of rain allows the soil to keep enough moisture during the critical periods of crop growing. According to FAO statistics (2013), rainfed agriculture accounts for about 60% of total production in sub-Saharan Africa. In this kind of agriculture, land management considerably conditions agricultural productivity. However, the ways to improve productivity of rainfed agriculture are limited to the extent that precipitation is subject to important seasonal variations, which is aggravated by climate change. The main climate change effects on water include the volume, intensity and variabilities of precipitation. Changes in the timing and distribution of the precipitation are associated with problems of more frequent and more severe floods and drought, depending on the region. Areas where precipitation is expected to occur are exposed to more frequent and severe floods and to increased erosion and reservoir sedimentation, while regions with lower precipitation face a decrease of water availability and severe drought (Bates et al., 2008). Even though there exists a high degree of uncertainty in forecasting future precipitation, increases in precipitation are mainly expected in high latitudes and reductions are expected in sub-tropical regions and lower latitudes. Similarly, environmental damage caused by irrigation raises serious concerns and creates doubts in many regions of the world about the sustainability of the practice.

In irrigated agriculture (non-rainfed), the water used to grow crops is partially or totally provided by man. Indeed, during rain seasons people use several methods to store runoff water in the soil, in lakes or retention dams, for use during dry seasons. In general, water for irrigation is withdrawn from water points (rivers, lakes or aquifers) and driven to crop area using appropriate transport infrastructure. To meet their needs of water, irrigated crops benefit from more or less reliable rainfall water and irrigation. Irrigation is an efficient management tool against uncertain precipitation. According to Fox and Rockström (2003) and Pathak et al. (2009), relying on irrigation as a complementary tool would be an interesting alternative option to reduce water deficits for rainfed crops in semi-arid areas.

Figure 1: Trends of irrigated and arable lands (in hectares)



Source: Computed by authors using FAO-database[1].

Sub-Saharan Africa alone accounts for 99% (3,884 km3) of the renewable water resources of the continent, but with a lower efficient utilization rate of 30%, compared to northern Africa where this rate is 69% with only 1% of the renewable water resources. Only 3% of this water is used for irrigation in sub-Saharan Africa, compared to northern Africa where this rate is 170% (FAO, 2011). Historically, the increase in irrigated agricultural land followed the same growth pace as the arable lands in sub-Saharan Africa (Figure 1). In contrast, in northern Africa, the increase of irrigated agricultural land was faster, meaning more important needs of water. The fact that the increase in irrigated agricultural land has the same growth pace as that of arable land shows the importance of water in the agricultural production process. The important shares of irrigated lands demonstrate the need to improve the use of water as an input in agriculture. Rhoades (1997) concluded that the increase of food production in developing countries should essentially come from irrigated agricultural lands.

However, water is a complex resource, unlike a stable resource over human lifetime like land. Water is produced in a dynamic cycle of rain-runoff water-evaporation, with important time and spatial variations, and quality variations that condition African production systems. Even though this could be a nuisance (in case of floods) for certain crops, efficient use of water remains a challenge for sustainable agriculture in Africa. A wide empirical review assessing agricultural productivity growth (Timmer, 1997; Irz et al., 2001; Pratt and Yu, 2009; Devkota and Upaghyay, 2013; Djoumessi , 2021, 2022) disregarded water endowment as an input in agricultural production. Very few studies (Wallace, 2000; Howell, 2001; Zwart and Bastiaanssen, 2004; Fereres and Soriano, 2007) have attempted to analyse the role of water use in agriculture. To the best of our knowledge, no study has so far attempted to analyse agricultural productivity growth, taking into account water endowment as an input, which was the main objective of this study.

2. Literature review

Productivity is an important indicator of improved economic performance of a country or region. Literature distinguishes two main measures for productivity growth: the partial measure of factor productivity and the total factor productivity (TFP). Many studies using different approaches have significantly underlined the importance of agricultural productivity as an important factor for reducing poverty. Datt and Ravallion (1998) found that yield per unit of land is statistically significant as a determinant cause of poverty reduction in India. Timmer (1998), and Devkota and Upadhyay (2013), used labour productivity as a measure, considered by Mellor (1963) as a better measure for productivity. Irz et al. (2001) found that the more direct contribution of growth in agriculture generates higher income for farmers. Gallup et al. (1998) found that an increase of 1% of agriculture in gross domestic product (GDP) leads to an increase of 1.61% of income for the poorest quintile. Pratt and Yu (2009) analysed the development of the agricultural TFP in sub-Saharan Africa over the past 40 years. They revealed a remarkable recovery in agricultural performance in the region between 1984 and 2003 after a long period of weaker and declining performance. According to these authors, this recovery was due to the improvement in production efficiency resulting from changes in the output structure and adjustments in the use of inputs.

Moreover, an important body of empirical works was devoted to analysing agricultural productivity, but few of these have considered the environmental objectives focusing on the use of water. McArthur and McCord (2017) estimated the role of agronomic inputs on the increase of yield in cereals. They found that fertilizers, improved seeds and water are the most important factors in yield increase. Their empirical analysis of the link between agricultural yield and growth shows that an increase by 50% of yield generates from 14% to 19 % increase in GDP per capita. Fereres and Soriano (2007) concluded that reducing water for irrigation helps address situations where water provision is restricted. According to Howell (2001), irrigated agricultural land can result in environmental degradation and compromise sustainability, if appropriate water management measures are not taken.

Sinclair et al. (1984) described efficiency in water use at different scales, from leaf to land. In simple terms, this study refers to harvesting yield for a unit of water used. Brown (1999) proposed a benchmark to define water productivity as the quantity of water needed to produce one unit of yield per crop, which is the long-term transpiration rate or the inverse of efficiency in water use (EWU). However, though these initiatives are attractive, they are not easy to materialize because many factors related to management may affect yield or vary considerably between irrigated agriculture and arid lands (Howell, 2001).

Globally, in irrigated and rainfed agriculture, only 10% to 30% of available water (rain, surface and underground water) is used by crops in the transpiration process. In arid and semi-arid areas, where water is scarce and population growth is high, that rate is close to 5% for rainfed crops. Wallace (2000) examined the efficiency of water use in agriculture. He concluded that there are many ways to improve water use. Zwart and Bastiaanssen (2004) assessed an average measure of productivity of rainfed crops on the basis of 85 well-documented sources. The analysis shows that it is still possible to maintain or increase agricultural production with less than 20% to 40% of water use. The variation of productivity of water in crop growth is attributed to: i) climate; ii) management of irrigation water; and iii) management of soils (nutrients). The authors concluded that productivity of water in crop growth may be considerably increased if irrigation is reduced and water deficit of crop growth is consequently reduced in a planned manner.

China and India, the two greatest producers and consumers globally of many agricultural products, already face severe water limitations in agricultural production, but both countries have launched programmes to stimulate production of biofuels. De Fraiture et al. (2007) explored the global implications of the increase in production of biofuels on water and land, focusing on these two important countries, using the WATERSIM model. They concluded that pressure on water resources would be so strong that, in China and India, policy decision-makers will probably not consider the biofuels options, at least those based on the important traditional crops.

According to Perry et al (2017), water productivity in agriculture may be improved in three ways: i) reducing the quantities used while maintaining the production level; ii) increasing agriculture production while using the same quantity of water; and iii) increasing production with reduced water use, which would be the ideal outcome. Many strategies have already been set up on the continent for sustainable agriculture to meet the increasing demand due to population growth, urbanization, agricultural intensification and inappropriate management of water resources. In Ethiopia, a model for evaluation and planning of water use has been developed to allow a rational allocation of water provision with the view to maximizing economic benefits (Gedefaw et al., 2019). Three alternative ways to manage irrigation with the rice intensification system have been evaluated on the ground against the conventional continuously flooded system used in Tanzania (Materu et al., 2018). Sekyi-Annan et al. (2018) showed that improvement of the timing for irrigation of tomatoes growing in dry seasons would lead to water savings of 130–1,325 mm compared to traditional irrigation practices; this experience further showed an increase of tomato yield of 4–14% in Ghana.

To sum up, these studies concluded that it would be advisable to: i) either reduce the irrigated areas or ii) limit cultivation of crops requiring high quantities of water. However, no study has considered water endowment as an input that should be included in the estimation of TFP in agriculture. Against this background, this study aimed to provide a better measure of agricultural productivity, and present the implications of efficient water use in agriculture.

3. Methodology

3.1. Econometric model

Two approaches are commonly used to measure TFP growth[2]: the Data Envelope Analysis (DEA) and the Stochastic Frontier Analysis (SFA). However, the DEA approach is the most commonly utilized, mainly because of the easier estimation techniques and the computing simplicity it offers. The key feature of the SFA analysis is that it is able to separate the statistical noise[3] from the inefficient effects, unlike the DEA approach which attributes any distance from the frontier to inefficiency. Like Coelli et al. (2002), Headey et al. (2010) examined the differences between the DEA and SFA approaches in the evaluation of agricultural TFP for 88 countries during the period 1970–2001. They found that the results of the SFA approach are more plausible than those of the DEA method. Several indices are used to evaluate the validity of the results obtained with the two methods: i) important volatility of the estimated average growth rate from one year to another; ii) the standard errors of the annual TFP growth rate of each country are around one-third of those obtained with DEA; and iii) a weak or zero correlation between the TFP growth and labour productivity rate in agriculture is obtained with the DEA method. It is this difference that motivated our choice to use SFA instead of DEA in this research to estimate TFP growth taking into account the natural capital.

From the outset, let us consider a production function of Cobb–Douglas type in which the agriculture output y_{jt} is produced with capital, k_{jt} and labour, l_{jt} for each country j at period t. To integrate the “natural capital” in the TFP estimation, we consider H_t as the water endowment in agriculture at period t, then the production function may be written as follows:

$$y_{jt} = e^{\pi+\alpha_0 t} k_{jt}^{\alpha_1} l_{jt}^{\alpha_2} h_{jt}^{\alpha_3} \tag{1}$$

where $\sum_{i=1}^{3} \alpha_i = 1$. The specification allows water endowment in agriculture to be considered as an input variable, in the case of Cobb–Douglas function. Expressing the variables in Equation 1 into their natural logarithm, we have the following new specification:

$$\ln y_{jt} = \pi + \alpha_0 t + \alpha_1 \ln k_{jt} + \alpha_2 \ln l_{jt} + \alpha_3 \ln h_{jt} \tag{2}$$

The estimation of Equation 2)in terms of growth rates[4] may be formulated as:

$$\frac{\dot{y}_{jt}}{y_{jt}} = \pi + \gamma_t + \left(\frac{\partial y}{\partial k}\frac{k_{jt}}{y_{jt}}\right)\frac{\dot{k}_{jt}}{k_{jt}} + \left(\frac{\partial y}{\partial l}\frac{l_{jt}}{y_{jt}}\right)\frac{\dot{l}_{jt}}{l_{jt}} + \left(\frac{\partial y}{\partial h}\frac{h_{jt}}{y_{jt}}\right)\frac{\dot{h}_{jt}}{h_{jt}} \tag{3}$$

where $\frac{\partial y}{\partial h}\frac{h_{jt}}{y_{jt}}$ is the measure of gain provided by the growth rate of water endowment in agriculture, and $\pi + \gamma_t$ is the technical progress growth rate (γ_t being a white noise with zero mean and constant variance) and is obtained as follows:

$$\pi + \gamma_t = \frac{\dot{y}_{jt}}{y_{jt}} - \left[\left(\frac{\partial y}{\partial k}\frac{k_{jt}}{y_{jt}}\right)\frac{\dot{k}_{jt}}{k_{jt}} + \left(\frac{\partial y}{\partial l}\frac{l_{jt}}{y_{jt}}\right)\frac{\dot{l}_{jt}}{l_{jt}} + \left(\frac{\partial y}{\partial h}\frac{h_{jt}}{y_{jt}}\right)\frac{\dot{h}_{jt}}{h_{jt}}\right] \tag{4}$$

The above difference is widely known in the literature as the “Solow residual”. This residual measures the production gains which are independently obtained from those obtained by a more intensive use of the production factors included in the function. Chambers (1988) explained that this residual expresses the ignorance of the other factors that contribute to production growth. Therefore many authors define this residual as the production “multifactorial productivity” or “total factor productivity” (TFP) that is expressed in the following specification:

$$tfp_{jt} = \frac{\dot{y}_{jt}}{y_{jt}} - \left[\alpha_1\frac{\dot{k}_{jt}}{k_{jt}} + \alpha_2\frac{\dot{l}_{jt}}{l_{jt}} + \alpha_3\frac{\dot{h}_{jt}}{h_{jt}}\right] \tag{5}$$

However, the assumption of the unit substitution elasticity between factors characterizing the Cobb–Douglas type function considerably limits the scope of the results of the estimation. It is possible to relax these restrictive assumptions and define a combination of production factors relying on a flexible production function allowing the approximation of all possible technologies. These may be considered as second order approximations, twice differentiable, of any technology (Fuss, 1978; Chambers, 1988). The concept of the linear flexibility form and its property to provide second order approximations was defined by Diewert (1992). The flexible form is the most widely utilized and was used in this study. It is the Translog representation and is specified as follows:

$$\begin{aligned}\mathrm{Ln}\, y_{jt} &= \alpha_0 + \alpha_1 \ln k_{jt} + \alpha_2 \ln l_{jt} + \alpha_3 \ln h_{jt} + \beta_1 \ln k_{jt} \ln l_{jt} + \beta_2 \ln k_{jt} \ln h_{jt} + \\ &\beta_3 \ln l_{jt} \ln h_{jt} + \beta_4 \ln k_{jt} \ln k_{jt} + \beta_5 \ln l_{jt} \ln l_{jt} + \beta_6 \ln h_{jt} \ln h_{jt}\end{aligned} \tag{6}$$

A general formulation is presented in the following equation:

$$\mathrm{Ln}\, y_{jt} = \alpha_0 + \sum \alpha_k \ln x_{ikt} + \sum\sum \alpha_{kh} \ln x_{ikt} \ln x_{iht} \tag{7}$$

where $X_t = (K_t, L_t, H_t)$ represents the vector of inputs at period *t* with the integration of water endowment in agriculture. Any technology that is explicitly represented in the production function will require an econometric analysis to measure the TFP growth. However, while this approach allows one to measure TFP, it cannot disentangle growth productivity due to pure technological change from changes due to efficiency (technical or scale efficiency). According to Boussemart et al. (2003), disregarding efficiency of production factors may lead to erroneous measure of production growth. A solution to this problem is to rely on the definition of an application framework of distance function introduced in the seminal work of Shepard (1953).

The distance function is the most important notion on which quantity indices, productivity indices and efficiency measures of production units are determined. The use of the Malmquist index[5] as a measure of TFP has undoubtedly become one of the most widely used measures following the seminal work of Fare et al.(1989). A distance function is defined for a given production technology and will allow one to measure to which extent the behaviour of a producer departs from an optimal production path. Taking a production technology defined on the basis of a set of outputs, P(x), representing the set of all the output vectors, y, which are obtained using the input vectors, X, that is: P(x)= { X $\in R_+$: x can produce y }, y $\in R_+$. In the case of a translog type function with three production factors, $X_t = (K_t, L_t, Ht)$ and only one product, $q_,$ we have the following equation:

$$P(x) = \{(K_{t,}\ L_t, H_t) \in R_+^3 \colon \alpha_0 + \alpha_1 \ln k_{jt} + \alpha_2 \ln l_{jt} + \alpha_3 \ln h_{jt} + \beta_1 \ln k_{jt} \ln l_{jt} + \beta_2 \ln k_{jt} \ln h_{jt} + \beta_3 \ln l_{jt} \ln h_{jt} + \beta_4 \ln k_{jt} \ln k_{jt} + \beta_5 \ln l_{jt} \ln l_{jt} + \beta_6 \ln h_{jt} \ln h_{jt} \geq \ln q_{jt}\}, q \in R_+. \tag{8}$$

Hence, P(x) is the set of combinations of production factors which allows the production of at least the quantity *q* (*q* is a fixed quantity) for a given time period. The distance function is defined on the whole set of outputs, P(x), as : $D_0(x, q) = \min \{ȝ : (q/ȝ) \in P(x)\}$.The distance function $D_0 (X, q) \leq 1$ if and only if $q \in P(x)$ and $D_0 (X,q) = 1$ if the vector of outputs, *q* is located on the frontier of production possibilities. Then the distance function of translog type can be defined as follows:

$$\ln D_0(q_{it}, x_{it}, t) = f(\alpha, X_{it}, t) + v_{it} - \ln q_{it}$$
$$= \alpha_0 + \textstyle\sum_{k=1}^{n} \alpha_k \ln x_{ikt} + \frac{1}{2} \sum_{k=1}^{n} \sum_{h=1}^{n} \alpha_{kh} \ln x_{ikt} \ln x_{iht} + \sum_{k=1}^{n} \alpha_{kt} t \ln x_{ikt} + \alpha_t t + \frac{1}{2} \alpha_{tt} t^2 - \ln q_{it} + v_{it} \tag{9}$$

where α is a vector of parameters, the random error term $v_{it} \sim iid\ N(0, \sigma_i^2)$. The stochastic model is:

$$\ln q_{it} = f(\alpha, x_{it}, t) + v_{it} - u_{it} \tag{10}$$

where u_{it} is a non-negative random variable obtained from a truncated-normal distribution (Battese and Coelli, 1992). This variable allows one to capture the inefficiency technical effects. It follows that the measure of technical efficiency is equal to the ratio between the actual output and the corresponding stochastic frontier output, therefore the technical efficiency is defined as follows:

$$TE = \frac{\exp\left(f(\alpha,X_{it},t)+v_{it}-u_{it}\right)}{\exp\left(f(\alpha,X_{it},t)+v_{it}\right)} = \exp(-u_{it}) \tag{11}$$

We estimate next the change in technical efficiency, (ΔTE), between two periods on the basis of the technical efficiency *TE,* following Equation 9:

$$\Delta TE = \alpha_t + \alpha_{tt}t + \sum_{k=1}^{n} \alpha_{kt} \ln x_{ikt} \tag{12}$$

3.2. Data and variables

The study sample comprised 19 sub-Saharan African countries[6] with data covering the period 1991–2014. In this study, the output (represented by the agricultural production index) and the inputs (labour, cultivated land, agricultural machinery and tractors, fertilizers and water endowment) used to estimate production function and TFP, were drawn from World Bank and the Food and Agriculture Organization of the United Nations (FAO) statistical databases. The construction of the variable representing water endowment for agriculture was defined as a combination of the *available water index* and the *irrigated agricultural lands*. The index of available water was estimated using the principal component approach (PCA) on the basis of three variables: the average annual rainfall, superficial waters and renewable water resources.

The data used for this analysis were collected as follows (Annex Table A1): *Agricultural production index* = the index of crop production represents the agricultural production of each year compared to the reference period of 2004 to 2006. This index reports data on the total set of crops, except forage crops. The groupings by regions and income of the production indices from FAO were calculated on the basis of underlying values in dollars and normalized with regard to the reference period of 2004 to 2006. Figure 2 shows that, on average, all the countries in the sample experienced a rapid increase in agricultural production but with wide variations. A rapid production growth was observed for most of the countries since the 2000s. *Labor:* corresponds to active population working in agricultural activities for each year and for each country. *Lands:* agricultural lands represent the share of the territory that is arable and which is cultivated or in pasturage on a permanent basis.

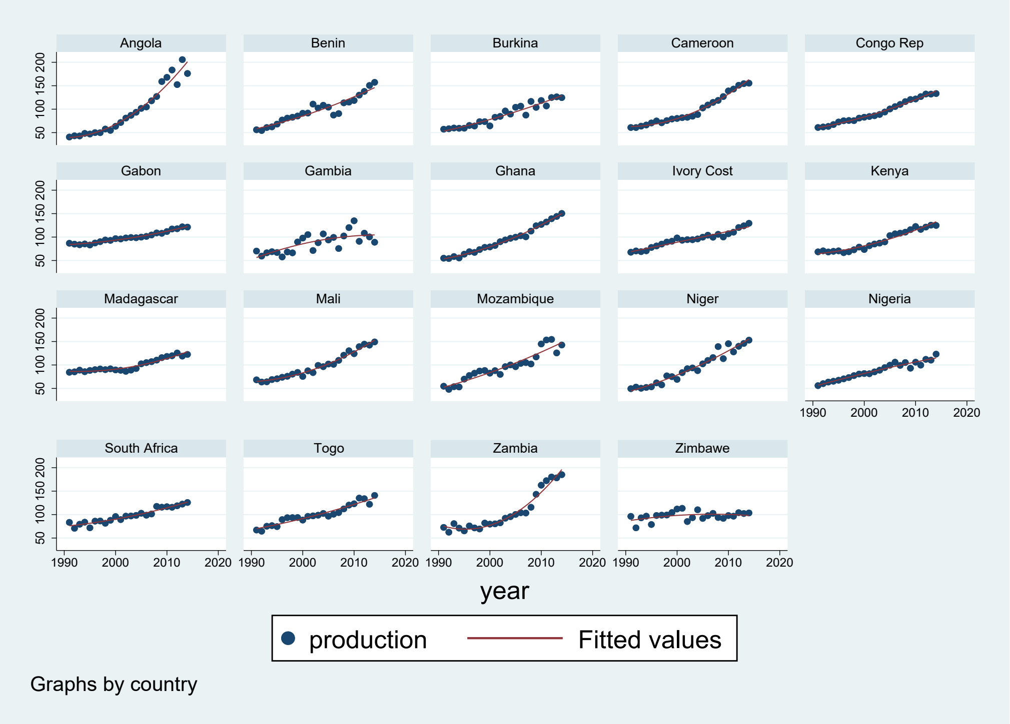
The arable lands include lands defined by FAO as lands with temporary crops (lands containing two crops are counted only once), temporary meadows for mowing and grazing, farmlands or vegetable gardens, and temporary fallow lands. The abandoned lands used for shifting cultivation are excluded from this evaluation. *Agricultural machinery and tractors* = the agricultural machinery refers to the number of tracked and wheeled tractors (excluding garden tractors) used in agriculture at the end of the year concerned or at the end of the first term of the subsequent year. *Fertilizers* = the consumption of fertilizers (100 g per hectare of arable land) measures the quantity of nutrients used per unit of arable land. The fertilizers included nitrogen, potassium or phosphate (notably natural lime phosphate fertilizers). *Irrigation* = the total fully irrigated agricultural lands. *Precipitations* = average annual rainfall within the country. *Surface waters* = total volume of surface waters within the country. *Renewable waters* = total volume of renewable water resources within the country. Table 1 describes the variables used to estimate the TFP growth, including water endowment as an input for agriculture.

Table 1: Descriptive statistics of the variables

Variables	Observations	Average	Std. Dev.	Min	Max
Output	456	95.687	26.948	40.7	205.68
Labour	456	49.511	23.275	0.091	85.975
Land	456	28099.56	25354.35	495	98125
Fertilizers	450	11.998	17.202	0.001	96.51
Machinery	322	2873.301	8611.659	2	70808
Irrigation	456	207.054	384.807	2	1670
Precipitations	456	1018.263	446.269	151	1831
Surface waters	456	93.724	98.753	1	332
Underground water	456	96.378	99.700	3	337

Source: Computed by authors

Figure 2: Trends of annual agricultural production by country



Source: Computed by authors using FAO database (2019).

4. Results and discussion

4.1. Principal component analysis (PCA)

This study used PCA from the works of Pearson (1901) and Hotelling (1933) to construct the index for the water variable. More advanced developments of PCA have been proposed by Choi et al. (2015). The PCA is generally considered as a statistical technique used to reduce the number of a set of correlated variables to a smaller number of non-correlated variables, called principal components.

The results of the PCA are presented in two panels (Table 2). The first panel presents the eigenvalues of the correlation matrix, from the highest to the smallest, and the second panel presents the corresponding eigenvectors. The eigenvalues are the variances of the principal components. The first principal component has a variance of 2.59, which explains 86.3 % of the total variance. The second principal component has a variance of 0.409, which explains 13.6% of the total variance. The Kaiser and Jolliffe's criteria are used to select the common factor (Churchill and Behan, 2010). We recommended selecting the principal component with an eigenvalue higher than one. Moreover, to support this choice, we computed the Kaiser–Meyer–Olkin criteria which give a total value of higher than 0.5 (Annex Table A3), which explains the correlation between production factors (Kaiser, 1974). Next, the downward trending curvature of the eigenvalues confirms the number of factors selected for PCA (Figure 3).

Table 2. Principal component analysis for the water index in agriculture

Principal components/correlations

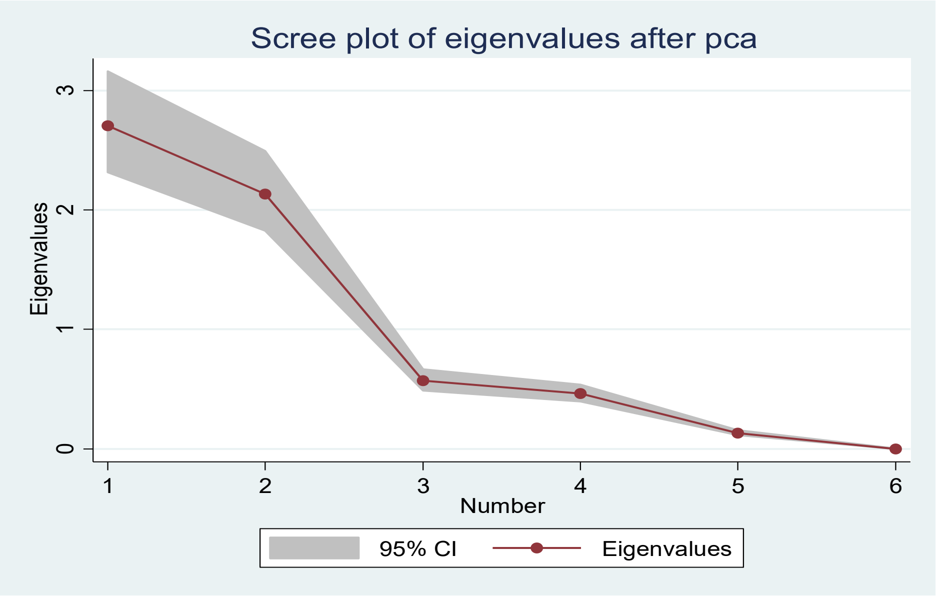
Components	Eigenvalues	Difference	Proportion	Cumulative
Comp1	2.590	2.181	0.863	0.863
Comp2	0.409	0.408	0.136	0.999
Comp3	0.000		0.000	1

Principal components (eigenvectors)

Variables	Comp1	Comp2	Comp3	Non- explained
Precipitations	0.520	0.853	0.013	0
Surface water	0.604	-0.357	-0.711	0
Underground water	0.602	-0.378	0.702	0

Source: Computed by authors.

Figure 3. Curvature of eigenvalues



Source: Computed by authors.

Table 3 presents the averages of the index of water and water endowment factor. The negative values appeared in the worst cases of the availability of water resource in those countries, as shown in the cases of Niger, Kenya, Burkina Faso, Zimbabwe etc. In other words, the available quantity of water is very critical in these countries that the use rate of water resource rapidly increased compared to the renewable rate. Madagascar had the highest potential in terms of water resource with an index estimated at 3.49, followed by Cameroon and Congo, with a water index of 2.81 and 2.27 respectively. The water endowment factor captures the quantity of water exclusively used in agriculture. Some countries currently use more than their potential in water resources, which is the case for South Africa, Mali, Zimbabwe etc.

Table 3: Average of water endowment variable by country

Country	Water index	Water endowment
Angola	0.616	51.257
Benin	-1.008	-15.870
Burkina	-1.347	-47.341
Côte d’Ivoire	0.145	10.582
Cameroon	2.818	75.036
Republic of Congo	2.277	4.554
Gabon	1.774	7.099
Ghana	-0.599	-14.578
The Gambia	-1.33	-3.692

Kenya	-1.360	-142.413
Madagascar	3.491	3792.406
Mali	-1.346	-322.237
Mozambique	0.061	7.025
Niger	-2.140	-166.799
Nigeria	1.643	447.834
South Africa	-1.232	-1824.623
Togo	-0.846	-5.924
Zambia	-0.178	-22.423
Zimbabwe	-1.434	-229.947

4.2. Water use and agriculture productivity: empirical evidence

4.2.1. Estimation of the stochastic production function

First, the stochastic production frontier (SPF) integrating water endowment as an input is jointly estimated using the Cobb–Douglas type function and translog function. All the variables are divided by their geometric mean. Therefore, the first order coefficients can be interpreted as elasticities of the agricultural production function estimated with regard to the geometric mean of the sample. The tests of the likelihood ratio, Akaike (AIC=Akaike Information Criteria) and Schwarz (SBIC or BIC=Bayesian Information Criteria) information criteria were used to evaluate the best specification of the functional form (the results are presented in detail in Annex Table A2). The two results of the likelihood ratio test and of the information criteria (AIC and BIC) rejected the Cobb–Douglas specification (restriction assumption), and the associated P (probability) value was 0.000. The SPF with water endowment as a regressor in the production function is estimated with the translog specification and the results are presented in Table 4.

The true fixed effects (TFE) and the true random effects (TRE) were introduced by Greene (2005a), to deal with the non-observed and invariant heterogeneity over time in the specification of the stochastic frontier. However, Wooldridge (2002) and, more recently, Lachaud et al. (2017) and Lachaud and Bravo-Ureta (2021) showed that the estimations with TFE are generally biased when the model includes invariant regressors over time or which vary slowly over time, as is the case for the water variable. As a result, the agricultural production model was estimated with a translog stochastic function with TRE of Greene (2005a) with the truncated normal distribution (Model 1) and half-normal distribution (Model 2) of errors, which capture the inefficiency.

A study by Battese and Tessema (1993) estimated SPF with panel data from three villages in India. They observed that the results on technical efficiency of individual farmers presented considerable variations, in the case of varying technical efficiencies over time as well as for the invariant technical efficiencies over time. Further, Battese and Coelli (1992) in the case of paddy farmers in a village in India, found that the technical efficiencies of the farmers were not invariant over time when the observation year was excluded from the stochastic frontier. This underlines the importance of the distribution and the specific technical efficiency over time. We have already chosen the specification for the varying inefficiency over time with the true random (Bellotti et al., 2013) and the results of the likelihood test ratio and the Bayesian information criteria of Akaike and Schvarz suggest that the truncated normal distribution fits the model better.

For the two models (1 and 2) we had almost similar results. The production factors, including water endowment, positively and significantly affected agricultural production, except for the labour variable. In order to underpin our results with robust results, any potential endogenous bias has been corrected in the following section.

Table 4: Results of the stochastic production frontier

Variables	(1) Truncated-normal	(2) Half-normal
t	0.0148***	0.0149***
	(0.00556)	(0.00561)
land	0.0997***	0.0911***
	(0.0791)	(0.0610)
labour	0.244	0.251
	(0.206)	(0.193)
machinery	0.0164***	0.0162***
	(0.00462)	(0.00474)
fertilizers	0.0735***	0.0720***
	(0.0204)	(0.0205)
water endowment	0.00819*	0.00915**
	(0.0179)	(0.0165)
t_2	0.000870**	0.000739*
	(0.000425)	(0.000421)
land_2	0.00354	0.000680
	(0.0260)	(0.0198)
labor_2	-0.192*	0.192**
	(0.110)	(0.0959)
MT_2	4.57e-06	3.40e-06
	(1.53e-05)	(1.53e-05)
fertilizers_2	0.00331	0.00290
	(0.00232)	(0.00221)
water endowment_2	7.09e-05	5.85e-05
	(0.000227)	(0.000217)
land_labour	0.0228	0.0200
	(0.0227)	(0.0242)
land_MT	-0.00145***	-0.00144***

	(0.000497)	(0.000509)
land_fertilizers	-0.0111***	-0.0108***
	(0.00318)	(0.00316)
land_water endowment	-0.00219	-0.00238
	(0.00359)	(0.00320)
land_t	0.00634***	0.00660***
	(0.000982)	(0.000970)
labour_MT	-0.00842***	-0.00838***
	(0.00232)	(0.00239)
labour_fertilizers	-0.00914	-0.00818
	(0.00859)	(0.00875)
water endowment_labour	0.00277	0.00263
	(0.00565)	(0.00569)
labor_t	0.00163	0.00184
	(0.00217)	(0.00218)
MT_fertilizers	0.000163	0.000159
	(0.000148)	(0.000149)
MT_water endowment	0.000198***	0.000196***
	(6.28e-05)	(6.39e-05)
MT_t	-7.25e-05	-5.73e-05
	(0.000143)	(0.000144)
fertilizers_water endowment	-0.000568**	-0.000574**
	(0.000261)	(0.000267)
fertilizers_t	-0.00277***	-0.00279***
	(0.000493)	(0.000487)
water endowment_t	-0.000221***	-0.000213***
	(7.81e-05)	(7.63e-05)
Constant	0.589***	0.547***
	(0.207)	(0.207)
Log (likelihood)	374.9293	374.325
Wald test	1490.83***	1444.50***
AIC	-687.8585	-686.651
BIC	-571.3326	-570.1251
Observations	317	317
Number of countries	19	19

Standard errors in parentheses

*** p < 0.01, ** p < 0.05, * p < 0.1

• Correcting for heteroskedasticity

Kumbhakar and Lovell (2000 T) had already underlined the presence of bias in the results from SPF when there is a non-controlled heterogeneity on u_t and v_t. To correct this bias, we used an extension of the estimation of the SPF model proposed by Belotti et al (2013); the results of the estimations are presented in Table 5.

The extension by Belotti et al. (2013) allows one to make four times fewer (or even no) iterations. The estimated parameters in the two models (following the truncated-normal distribution or half-normal distribution (Greene, 2005b)) are almost identical. The results showed that the estimated values of the production elasticity with regard to the classical inputs, including labour and water endowment for agriculture, were positive and significant. The model meets the conditions for monotonicity and quasi-concavity, as all the coefficients for level inputs are positive as predicted by Kumbhakar et al. (2015). However, as can be seen in Figure 4, water resources for agriculture dropped in a persistent manner. Nevertheless, its impact on the increase of agricultural production remained positive and significant.

The decline of the water resource factor on the continent must be considered as a warning signal. This decline should encourage all stakeholders to better manage this resource. The average decline of the water resources for agriculture was estimated at -0.07% per year during the period covered by the study. If only 2002–2012 is considered, the average was estimated at -0.05% per year. This represents a significant improvement in the management of water resources since the 2000s, but the change remains insufficient. In the case of production of citrus fruits in Tunisia, Dhehibi et al. (2007) observed that the efficiency of irrigation water is lower than the average of the technical efficiency, suggesting that the same volume of production could be obtained with the same quantity of inputs but with 47% less water. The improvement of efficiency in water use in agriculture strongly depends on investments by farms to improve the management of soils and water, according to a report by the World Bank (2020). Those options include the improvement in water distribution systems to deliver an appropriate service to demand, and the use of advanced technologies to improve water efficiency and productivity in agriculture. These shortcomings are the main causes of the downward trend of water availability over time that affects yield in crops consuming high quantities of water in sub-Saharan Africa. However, crop varieties that are sensitive to day duration (90–120 days) allow crops such as wheat, rice and maize developed during the Green Revolution to increase water productivity, as they are resistant to the droughts of end seasons which affect flowering and crop grain development. Water productivity with varieties of modern rice is three times higher than that of traditional varieties (Tuong, 1999).

Table 5: Results of stochastic production frontier with correction for heteroscedasticity

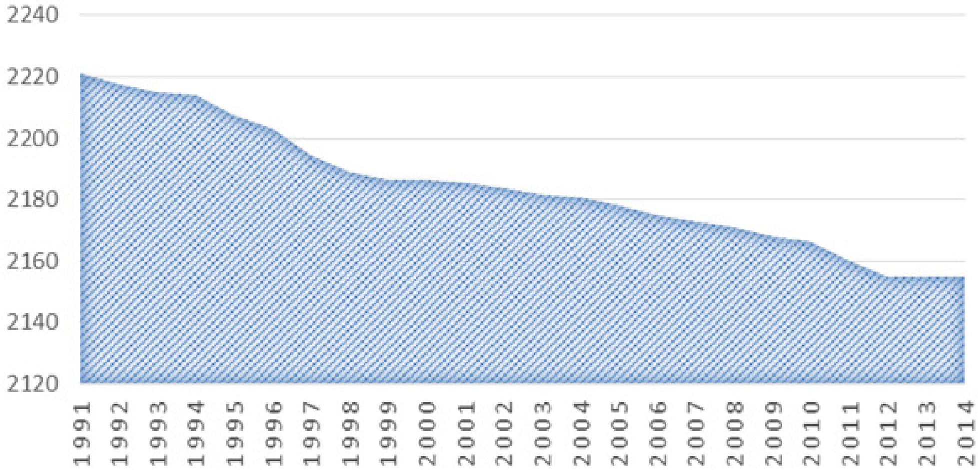
Variables	Stochastic production frontier (truncated-normal)		
t	0.0204***	Land_fertilizers	0.00376**
	(0.00555)		(0.00338)
land	0.474***	land_water endowment	-0.00519
	(0.253)		(0.00364)
labour	1.065***	land_t	0.00558***
	(0.225)		(0.00124)
machinery	0.0215***	labour_MT	-0.0111***

	(0.00439)		(0.00222)
fertilizers	0.0165**	labour_fertilizers	-0.000298
	(0.0214)		(0.00823)
Water endowment	0.0324***	water endowment_ labour	0.00407***
	(0.0202)		(0.00961)
t_2	0.00144***	labour_t	-0.00495**
	(0.000411)		(0.00218)
land_2	-0.210**	MT_fertilizers	8.19e-05
	(0.0868)		(0.000130)
landl_2	-0.874***	MC_water endowment	0.000251***
	(0.130)		(5.90e-05)
MT_2	1.06e-05	MT_t	-0.000238
	(1.50e-05)		(0.000150)
Fertilizers_2	0.00242	fertilizers_water endowment	-0.000303
	(0.00240)		(0.000278)
Water endowment_2	-0.000226	fertilizers_t	-0.000878*
	(0.000596)		(0.000522)
Land_labour	0.126**	water endowment_t	-0.000280***
	(0.0637)		(8.96e-05)
land_MT	-0.00135***	Constant	1.217
	(0.000444)		(2.569)
Observations	317	Log (likelihood)	423.8549
Number of countries	19	Wald test	2045.54***

Standard errors between brackets

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Figure 4: Trends of water endowment for agriculture in sub-Saharan Africa (1991–2014)



Source: Computed by authors.

4.2.2. Total factor productivity growth with decomposition and comparison

Table 6 presents the average results of TFP, including water input and its components for each year of the sample.

The data show that TFP with water endowment is mainly due to changes in technical efficiency (TEFF), followed by technical change (TC). However, the change in scale efficiency has been mostly a drag on the increase of TPF for most of the countries.

Indeed, that productivity in the African agriculture sector is based on the efficient use of production factors, with a significant change in technical efficiency. However, taking into account the management of water resources in agriculture, it can be seen that the technical efficiency followed by technological change would have mainly contributed to the increase in agricultural productivity over the whole study period. This includes the efficient use of irrigation systems that save water while smoothing the quantities produced during the year. African agriculture mainly comprises small-scale farmers who are mostly poor and marginalized and therefore experience shortages of water to irrigate their crops when needed. This generally leads to a reduction in productivity and agricultural incomes, or even a total loss of crops and capital invested in these crops. Another consequence of the scarcity of water is the high concentration of salts in the soil, which considerably reduces future productivity or forces farmers to abandon their land (Seckler, et al. 2003).

The key initiative to increase agricultural productivity of water use in agriculture is conditioned by the increase in the efficient transmission of the irrigation system. Molden et al. (2010) have shown that the increase of the uniformity and efficiency in irrigation presents some advantages for agricultural production, to the extent that it allows a reduction in non-productive evaporation, the irrecoverable infiltration and return flows, in the presence of shallow saline ground waters.

Lastly, the weak scale change, meaning weak land coverage, remained relatively constant during the period covered by the study. A comparison between the components of the TFP and water endowment showed that technical efficiency is the main determinant of the TFP growth during the sample period. In contrast, the technological change varied a little and remained almost constant. Regarding the development of scale efficiency, it showed a weaker contribution, was non-existent most of the time and was often negative.

More specifically, the average growth of TFP taking into account water endowment in our sample from 1991 to 2001 was negative and estimated at -0.44 % per year. This result is considerably lower than the growth rate obtained excluding the water endowment regressor during that period. The annual average growth of the traditional TFP estimated for that period is around 0.5% and 1% (Coelli and Rao, 2005; Pratt and Yu, 2012). When data from 2002 to 2012 are considered, the average annual growth of agricultural productivity with water endowment was positive and estimated at 0.36% for the countries included in the sample. This shows a clear improvement with regard to the average growth of the previous decade, but it remains lower than unity. This contrasts with the average annual growth rate of TFP, excluding water endowment in agriculture, which would have been higher than unity according to Headey et al. (2010). This last result shows an overvaluation of the productivity growth rate in agriculture when the water endowment factor is not included in the production function as an input.

Table 6: Distribution of TFP indices including water endowment and its components per year

Year	TFP	TC		Scale		Teff	
-	-	-	%	-	%	-	%
1992	1.086048	0.0239956	2.2094426	0.0635073	5.8475608	0.9985448	91.942997
1993	1.046399	0.0239322	2.2871008	0.0239184	2.285782	0.9985481	95.4270885
1994	1.026874	0.0250069	2.4352452	0.003321	0.3234087	0.9985462	97.2413558
1995	1.018155	0.0259301	2.5467733	-0.0063194	-0.6206717	0.9985439	98.0738591
1996	1.021694	0.0260475	2.5494424	-0.0029036	-0.2841947	0.9985497	97.7347131
1997	1.005973	0.0266423	2.648411	-0.0192184	-1.910429	0.9985492	99.2620279
1998	1.020545	0.0270485	2.6503976	-0.005055	-0.4953236	0.9985517	97.8449456
1999	1.016976	0.0273697	2.6912828	-0.0089482	-0.8798831	0.9985541	98.188561
2000	1.046739	0.0277778	2.6537465	0.020411	1.9499608	0.99855	95.3962736
2001	0.9167676	0.0278432	3.0371056	-0.1096294	-11.958254	0.9985538	108.921149
2002	1.037868	0.0274975	2.6494217	0.0118249	1.1393453	0.9985456	96.211233
2003	1.10122	0.0248555	2.2570876	0.0778173	7.0664627	0.998547	90.6764316

2004	1.033967	0.0252408	2.4411611	0.0101783	0.9843931	0.9985481	96.5744651
2005	0.8937767	0.0257841	2.8848481	-0.1305564	-14.607273	0.998549	111.722425
2006	1.052531	0.0270541	2.5703851	0.0269308	2.5586705	0.9985457	94.8709064
2007	0.9585185	0.0262706	2.7407504	-0.0662885	-6.9157246	0.9985364	104.174974
2008	1.040393	0.0263485	2.5325526	0.0154932	1.489168	0.9985514	95.978289
2009	1.045638	0.0274436	2.6245794	0.0196429	1.8785564	0.9985511	95.4968259
2010	0.9335345	0.0282443	3.0255229	-0.0932714	-9.9912108	0.9985617	106.965699
2011	1.023914	0.0279379	2.7285397	-0.0025765	-0.2516325	0.9985522	97.5230537
2012	1.008802	0.0277914	2.7548914	-0.0175431	-1.7390033	0.9985534	98.9840821
2013	1.00727	0.0276304	2.7430977	-0.0189055	-1.8769049	0.9985455	99.1338469
2014	1.028424	0.024825	2.4138877	0.0050576	0.4917816	0.998541	97.0942918

Notes: TFP = total factor productivity; TC = technical change; Teff = technical efficiency change; Scale = scale efficiency change.

However, the fact that the average growth rate of 2002–2012 (0.36%) was higher than that of the previous decade (-0.44%) can also be explained by a better management of water resources. The average reduction of water resources amounted to -0.08 % per year between 1991 and 2001 and was -0.05% per year between 2002 and 2012, which is also considerably lower than the average of the full sample period, that is -0.07%. This shows the persistence of a slow increase in TFP accompanied by an efficient use of production factors along with advanced technologies, that led to water savings during 2002–2012.

If the full sample period covered by the study is considered, that is 1991–2014, the average growth rate of TFP, including water endowment, is estimated at 0.045% per year, which remains lower than the usual TFP growth rates calculated without considering water resources. That growth rate is mainly determined by the increase of better practices in management and agricultural innovations. For the way forward, sub-Saharan Africa should direct efforts towards optimal coverage of agricultural lands.

5. Conclusion

To sum up, the main objective of the study was to examine the agricultural productivity taking into account water endowment as an input for a sample of 19 sub-Saharan African countries with a panel data set covering the period 1991–2014. The results of the SPF model show that the estimated values of the output elasticities with regard to the traditional production factors and water endowment in agriculture, have a positive and significant effect on the agricultural production growth after correction for the indigeneity bias. The average growth rate of TPF taking into account water endowment as an input is estimated at 0.045% per year, which is considerably lower than the traditional TPF growth (amounting to 1%). From 1991 to 2001, the average annual growth rate of the TPF with water endowment as a production factor has been estimated at -0.44%, mainly due to the poor management of crops. In the subsequent period of 2002–2012, the agricultural productivity growth rate has registered a fast increase estimated at 0.36 %. The average growth rate of the TFP with water endowment during the 2002–2012 period is due to the significant increase of agricultural best practices followed by technological advances that led to water savings. The average water savings in agriculture amounted to -0.08% per year between 1991 and 2001; this rate stood at -0.05% between 2001 and 2012. These results show the significant impact of water efficiency per unit of agricultural production. Therefore this study recommends that public or private decision makers focus more on efficient management of water resources to support sustainable agriculture. This includes improved irrigation technology, which leads to water savings. Among those innovations, the following can be mentioned: the pipeline distribution systems, the adoption of pressure systems for sprinklers, and drip irrigation or a system that delivers water directly to plant roots. In each case, the aim is to substitute the wasteful traditional irrigation system using new technologies that maximize the benefit of water use for each crop.

Notes

1 https://www.fao.org/faostat/en/#home.

2 TFP is obtained from at least two of the three following components: technical efficiency, scale efficiency and technical progress, derived from DEA and SFA methods.

3 Notably the measurement errors and variable omissions.

4 In an economy that works in a pure and perfect competition environment, production factors are remunerated with regard to their marginal productivity. This practice implies, according to Ten Raa and Mohnen (2002), that the Solow residual includes an additional element which is the deviation of the economy from the equilibrium situation. A solution to the problem would be an estimation of the equation with growth rates (Klein & Özmucur, 2003).

5 The Malmquist productivity index, derived from the works of the mathematician Sten Malmquist (1953), allows one to identify the share of the change in productivity attributable to technical change without needing the information on prices, which very often are the constitute omitted and questionable data because of their volatility.

6 Angola, Benin, Burkina, Cameroon, Congo Rep, Gabon, Gambia, Ghana, Ivory Cost, Kenya, Madagascar, Mali, Mozambique, Niger, Nigeria, South Africa, Togo, Zambia, Zimbabwe

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Annex A: Additional analysis

Annex Table A1: Description and sources of variables

Variable	Source	Definition (unit)
Agricultural production	FAO	An index measuring agricultural production for each year with regard to the reference period of 2004 to 2006 (in US dollar)
Labor	FAO	The active population engaged in agricultural activities (number of individuals)
Land	FAO	The share of area that is arable and used for agriculture or pasturage on a permanent basis (ha)
Machinery and tractors	World Bank and FAO	Number of tracked and wheeled tractors (excluding garden tractors) used for agriculture
Fertilizers	FAO	the quantity of nutrient elements used per unit of arable land (100 g/ha)
Irrigation	FAO	The total area of really irrigated agricultural lands (ha)
Precipitations	FAO	Average of annual rainfall
Superficial waters	FAO	Total volume of surface waters (m3/year)
Renewable waters	FAO	Total volume of renewable water resources (m3/year)

Annex Table A2: Results of the stochastic production frontier with both specification forms

	(1)	(2)
Variables	SPF Cobb–Douglas	SPF Translog
t		0.0149***
		(0.00561)
land	0.0478***	0.0911
	(0.0113)	(0.0610)
labour	0.0144	0.251
	(0.0229)	(0.193)
machinery	0.00154***	0.0162***
	(0.000461)	(0.00474)
fertilizers	0.0181***	0.0720***
	(0.00337)	(0.0205)
water endowment	0.00206***	0.00915***
	(0.000720)	(0.0165)
t_2		0.000739*
		(0.000421)
land_2		0.000680

		(0.0198)
labour_2		0.192**
		(0.0959)
MT_2		3.40e-06
		(1.53e-05)
fertilizers_2		0.00290
		(0.00221)
water endowment_2		5.85e-05
		(0.000217)
land_labor		0.0200
		(0.0242)
land_MT		-0.00144***
		(0.000509)
land_fertilizers		-0.0108***
		(0.00316)
land_water endowment		-0.00238
		(0.00320)
land_t		0.00660***
		(0.000970)
labour_MT		-0.00838***
		(0.00239)
labour_fertilizers		-0.00818
		(0.00875)
water endowment_labour		0.00263
		(0.00569)
labour_t		0.00184
		(0.00218)
MT_fertilizers		0.000159
		(0.000149)
MT_water endowment		0.000196***
		(6.39e-05)
MT_t		-5.73e-05
		(0.000144)
fertilizers_water endowment		-0.000574**
		(0.000267)
Constant	0.933***	0.547***
	(0.122)	(0.207)
AIC	-231.707	-686.651
BIC	-197.8769	-570.1251
Likelihood test ratio		498.94***
Observations	317	317
Number of countries	19	19

Standard errors between brackets

*** p<0,01, ** p<0,05, * p<0,1

Annex Table A3: Sample fit measure of Kaiser–Meyer–Olkin

Variable	kmo
precipitations	0.5917
surface water	0.5256
underground waters	0.5266
overall	0.5407

Annex Table A4: Results of the stochastic production frontier with all the variables

Variables	(1) Truncated-normal	(6) Half-normal
labour	0.0181	0.0200
	(0.0282)	(0.0296)
land	0.0523***	0.0528***
	(0.0157)	(0.0168)
fertilizers	0.0136***	0.0137***
	(0.00416)	(0.00432)
machinery_tr	0.00127***	0.00129***
	(0.000484)	(0.000492)
precipitations	0.0517	0.0547
	(0.0587)	(0.0594)
surface waters	-0.272	-0.253
	(0.293)	(0.288)
underground waters	0.303	0.282
	(0.323)	(0.318)
irrigated lands	0.00424***	0.00421***
	(0.00347)	(0.00335)
Constant	0.879***	0.881***
	(0.0868)	(0.135)
Likelihood test ratio	123.2206	122.6738
Wald test	31.67***	29.77***
Observations	317	317
Number of countries	19	19

Standard errors in parentheses

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$

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