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Exploring the drivers of technical efficiency in Senegal's agricultural production sector

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Most agricultural farmers in Senegal make limited use of key agricultural inputs such as fertilizers, certified seeds, irrigation, mechanization and pesticides. Such situation happens in a context where most farmers are exposed to droughts, land degradation, and erratic climatic shocks. These factors typically lead to negative effects on technical efficiency, and therefore unfavorable outcome results in terms of food production, income, and food security. This paper uses the Stochastic Production Frontier model to determine the efficiency of agricultural production in Senegal. The results show that Senegalese agricultural households produce 53% of the output that could potentially be produced with the observed input levels and their available technology. Main drivers of technical inefficiency behind this finding were limited use of fertilizers (both organic and inorganic), low levels of mechanization in agricultural practices, and high vulnerability to droughts, which significantly limit technical efficiency in agricultural production. The implication in terms of agricultural policy suggests that improving technical efficiency would require a combination of measures oriented to promote a wider use of fertilizers, promotion of a more mechanized and equipped agricultural processes, and overall to implement mechanisms to mitigate or reduce the impacts of droughts on agricultural production.

Key words: Technical efficiency, agricultural production, agricultural households, Senegal.

INTRODUCTION

Senegal produces a relatively wide variety of food security agricultural output such as millet, rice, maize, and sorghum (DAPSA, 2020), as well as some cash crops such as peanuts, sugarcane, cotton, a variety of fruits (e.g. watermelon and mango) and vegetables (e.g. cowpea and tomato).

Most agricultural farmers (95%) obtain such production from less than 2 ha of agricultural land (World Bank, 2021). Senegalese farmers are exposed to climatic shocks, droughts, land degradation, and low resilience

(WFP, 2022). In Senegal, land degradation affects 64% of arable land, with 74% of this degradation being caused by erosion and the rest by salinization (AGNES, 2020). The use of agricultural inputs such as fertilizers, certified seeds, irrigation, mechanization and pesticides is limited (DAPSA, 2020). These factors have negative effects on technical efficiency in terms of how well farmers are able to utilize these inputs. Such ability is an important determinant of the quantity of output they are capable to produce.

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Low technical efficiency leads to low agricultural productivity and low agricultural production. In face of an ever-increasing population growth (IFPRI, 2016), Senegal's condition of net food-importing country becomes exacerbated, particularly in rice which represents almost 65% of cereal imports, and is the population's main staple crop (CIAT and BFS/USAID, 2016).

A direct result of low technical efficiency is low domestic production, which generates the country's considerable food gaps. Higher technical efficiency would lead to more production, to higher domestic food supply, and possible to a lesser dependence on food imports, which would help reducing vulnerability to foreign shocks, particularly those related to food prices (IFPRI, 2016). Higher efficiency would also lead to improved food security by increasing the availability and affordability of agricultural products, and to increase agricultural incomes.

Hence, improving efficiency in the agricultural sector, which employs a large segment of the population, is a major concern in the country. The Programme d'Accélération de la Cadence de l'Agriculture Sénégalaise (PRACAS) and the Plan Sénégal Émergent have highlighted the importance of improving technical efficiency and agricultural productivity of farmers, particularly through the adoption of technologies and good agricultural practices.

Currently, no comprehensive study exists measuring technical efficiency for the Senegalese agricultural sector, a gap that this study attempts to fill. In this context, the purpose of this paper was to determine the underlying driving factors of technical efficiency in Senegalese agricultural production, which can provide directions to promote adequate support to enhance development potentials of farm production. Data for the analysis came from the Annual Agricultural Survey (AAS) corresponding to the 2017/2018 agricultural period. This data is a cross-sectional microdata which was collected by Direction de l'Analyse, de la Prévision et des Statistiques Agricoles (DAPSA) - Ministry of Agriculture and Rural Equipment, with technical support from the AGRISurvey Programme. The Stochastic Production Frontier (SPF) approach was used to achieve the objective of the study.

The main limitation of the study is obtaining primary information since it comes from surveys. As is normal in econometrics, some observations were excluded, which were considered outliers. It is possible that in subsequent studies the stochastic frontier model could be determined at the specific product level, depending on the interest of the beneficiaries, the policy objectives and the availability of information at a disaggregated level.

METHODOLOGY

Senegal, with a total population of 17.2 million people of which 52.8% lived in rural areas in 2021 (FAOSTAT, 2022), lies within the drought-prone Sahel region. The country has about 196,000 km² of

land, of which only 16.3% (3.2 million ha) is arable land (FAOSTAT, 2022), and the rest are deserts (over one-third of the country's total area), savannas, steppes and woodlands. Agricultural production from that limited area is extremely important for the country. Agriculture contributed in 2020 with 17% of total GDP (WDI, 2022), with 36% of the national labor force (World Bank, 2020), and with 69% of rural employment (World Bank, 2020).

Technical efficiency (TE)

Technical efficiency in agricultural production is a subject of long-standing analysis in agricultural economics. Efficiency analysis focusses on the possibility of producing a maximum level of output from a given set of resources or producing a certain level of output at the lowest possible cost (Russell and Young, 1983). That is, technical efficiency analyzes the distance between the actual production level obtained, and the maximum production that could be obtained from an adequate and optimal combination of productive factors available. Generally, the measurement of technical efficiency is expressed through a production function bounded by a maximum production frontier.

This paper uses the Stochastic Production Frontier (SPF) model to determine technical efficiency of agricultural production in Senegal. The SPF model for cross-sectional data was simultaneously developed by Aigner, Lovell and Schmidt (1977) and Meeusen and Van den Broeck (1977). The starting point of this model is defined by a parametric production function of the Cobb Douglas type¹:

$$Y_i = f(X_i\beta) e^{\varepsilon} \quad (1)$$

where Y_i = Is the production of the i -th unit, X_i = Is a vector $k + 1$ with values corresponding to the inputs of the production function (including the constant term), β = Is a vector of the parameters to be estimated, and ε = Error term.

The error term ε , is decomposed as follows:

$$\varepsilon = (v_i - u_i) \quad (2)$$

The u_i component is the non-negative random variable associated with technical inefficiency in production and must be inferred from the compounded term $(v_i - u_i)$. To break down u_i and establish which part corresponds to inherent error of the model, and which part corresponds to inefficiency, some assumptions about the distribution of both components must be established. The error component v_i is assumed to be independent and identically distributed with a normal distribution $N(0, \sigma_v^2)$. Following Stevenson (1980), the error component u_i is assumed to have a truncated normal distribution $u_i \sim N(\mu, \sigma_u^2)$, truncated in 0. Following Battese and Coelli (1992), the technical inefficiency component was assumed to be a non-negative random variable distributed independently, but not identically following a truncated normal:

$$u_i \sim N(Z_i\delta, \sigma_u^2) \quad (3)$$

$$u_i = Z_i\delta + W \quad (4)$$

¹ For the present analysis, the Cobb-Douglas functional form is chosen since it allows obtaining the elasticities of the inputs with respect to the product and with respect to the production frontier.

where Z_i is a vector ($M \times 1$) that represents all the observable variables that explain technical inefficiency, and δ is a vector ($1 \times M$) with the inefficiency parameters to be estimated, including a constant. Under these characteristics, the model does not consider neither the possible correlation between the stochastic errors nor the presence of heteroscedasticity in the two error components. The model is estimated by maximum likelihood method. Under these characteristics, Battese and Corra (1977) suggest replacing σ_v^2 and σ_u^2 by $\sigma_S^2 = \sigma_v^2 + \sigma_u^2$, and using the parameter γ instead of the parameter λ . The parameter γ , explained by the variance of the inefficiencies, is obtained from the following expression:

$$\gamma = \sigma_u^2 / \sigma_S^2 \tag{5}$$

The reason these authors argue for replacing parameter λ is that it limits the possible values in the maximization of the log-likelihood function, since it varies between zero and one, while the parameter γ can be equal to any non-negative value. Thus, if $\gamma = 0$ any deviation from the frontier is due to white noise, while if $\gamma = 1$ all deviations from the frontier are explained by the presence of technical inefficiency.

Model of technical efficiency

Technical efficiency (TE) is defined as the relationship between the observed production Y_i and the corresponding frontier production $f(X_i\beta)e^{v_i}$ conditioned to the levels of inputs used by the farm (Russell and Young, 1983). In this context, the Production Frontier is represented by:

$$f(X_i\beta)e^{v_i} \tag{6}$$

Replacing in Equation 1, the TE is determined as follows:

$$TE = \frac{Y_i}{f(x_i,\beta) e^{v_i}} = \frac{f(X_i\beta)e^{(v_i-u_i)}}{f(x_i,\beta) e^{v_i}} \tag{7}$$

$$TE = e^{-u_i} \tag{8}$$

The stochastic frontier estimated with the Maximum Likelihood method results in the envelope of all observations. With the corresponding residuals it is possible to calculate the individual levels of technical efficiency, which per construction are $0 < TE \leq 1$. For the calculation of the model, it is necessary to assume a distribution for the two error elements. Subsequently, all the estimators of the technological parameters ($Y_i = f(X_i\beta) e^{(\varepsilon)}$), the efficiency parameters (u_i), the variance ($\sigma_S^2 = \sigma_v^2 + \sigma_u^2$) and the parameter γ are estimated, thus obtaining consistent and asymptotically efficient estimators.

Hypothesis testing

To carry out the hypothesis test regarding whether the model parameters should be estimated through ordinary least squares or maximum likelihood method, the following likelihood ratio test was used:

$$LR = -2[\ln\{LH_0\} - \ln\{LH_1\}] \tag{9}$$

where (LH_0) corresponds to the value of the logarithmic likelihood function for the restricted model calculated using a linear regression model (Annex 1²), and (LH_1) corresponds to the value of the logarithmic likelihood function of the general SPF model. This test is asymptotically distributed as a Chi-square distribution with degrees of freedom equal to the difference between the numbers of parameters estimated under both hypotheses, that is, the technical inefficiency parameters.

The null hypothesis reflects that all the parameters of the model are equal to zero, which means that there are no deviations from the production frontier due to inefficiency, but only to random errors. In this case, the model would be equivalent to a traditional production function (or "mean response"), efficiently estimable through ordinary least squares. But if the null hypothesis is rejected, it means that there are technical inefficiency effects and therefore, the Stochastic Frontier model calculated by Maximum Likelihood is applicable. Annex 2 shows the result of the hypothesis testing exercise.

Specification of the econometrical model

To carry out the analysis of the technical efficiency of agricultural production in Senegal, the SPF model developed by Battese and Coelli (1995) was followed. They assumed that the component of technical inefficiency is a non-negative random variable distributed independently, but not identically following a Truncated Normal distribution.

SPF model is as follows:

$$\ln Y_i = \beta_0 + \sum_{i=1}^5 \beta_i \ln X_i + v_i - u_i \tag{10}$$

or

$$\ln Y = \beta_0 + \beta_1 \ln SUP + \beta_2 \ln MEC + \beta_3 \ln SEM + \beta_4 \ln FERT + \beta_5 \ln L_1 + v_i - u_i \tag{11}$$

where Y = Gross Value of Agricultural Production per household, SUP = Total cultivated area per household, MEC = Total cost of acquisition of Machinery and Equipment per household, SEM = Total cost of acquiring seeds per household, $FERT$ = Total cost of acquiring fertilizers per household and L_1 = Average number of days of family labor per household.

In this functional form, gross value of agricultural production per household was chosen as dependent variable, while cultivated area, cost of acquisition of machinery and equipment, cost of acquiring seeds, cost of acquiring fertilizers, and family labor as the independent variables.

Technical inefficiency model is as follows:

$$u_i = \delta_0 + \sum_{i=1}^6 \delta_i Z_i + W \tag{12}$$

or

$$u_1 = \delta_0 + \delta_1 SEQ + \delta_2 FERT_1 + \delta_3 SEM_1 + \delta_4 MEC_1 + \delta_5 CAP + \delta_6 DPP + W_1 \tag{13}$$

where U_i = Technical inefficiency, SEQ = Drought (proxy of climatic effects) (1= risk of drought; 2= no risk), $FERT_1$ = Use of fertilizers (1= applies fertilizers; 2= does not apply), SEM_1 = Use of certified/improved seeds (1= use; 2 = no use), MEC_1 = Use of machinery in agricultural activities (1= use; 2= no use), CAP = Specialized training of the household head (1=trained; 2= not

² In Stata the calculation is made through the generalized linear model explained in Annex 1,

Table 1. Technical information of the 2017/2018 AAS microdata.

Country	Senegal
Institution	Direction de l'Analyse, de la Prévision et des Statistiques (DAPSA)
Database	Annual Agricultural Survey 2017/2018
Reference period	Started: June 2017-Ended: January 2018
Unit of analysis	Agricultural Households and plots
Geographic coverage	The survey covers all the departments of Senegal, with the exception of Dakar, Guédiawaye and Pikine
Universe	The survey covers agricultural households in 42 departments of the country and 14 regions
Sample size	5,358 agricultural households
Final sample for the analysis	1,029 observations (19.2%)
Type of microdata	Quantitative and qualitative cross-sectional microdata
Econometric packages	Stata 16

Sample size of 1,029 households were selected based on the number of cases that had information about specific variables of interest, such as fertilizers, certified seeds, irrigation, mechanization, pesticides, training of the household head, and property of the parcel.

Source: Own elaboration based on microdata from AAS 2017/2018.

trained), DPP = Property of the parcel (1= own; 2= other) and W_i = Random variable.

The inefficiency model used dummy variables of drought (proxy of climatic effects), fertilizers, certified/improved seeds, machinery, specialized training, and property as the independent or explanatory variables, while technical inefficiency was the dependent variable.

Description of variables

Microdata for the analysis came from the 2017/2018 Annual Agricultural Survey (2017/2018 AAS), which is an annual national level survey collected, processed, analyzed and disseminated by DAPSA - Ministry of Agriculture and Rural Equipment. Table 1 presents technical information related to reference period, unit of analysis, geographic coverage, sample size and other technical inputs that were used in this research³.

The structural variables used in the stochastic frontier model and in the technical inefficiency model are shown in Table 2. Due to the existing variability in main structural variables (that is, Gross Value of Production per family, Total cultivated area, Total cost of acquisition of Machinery and Equipment, Total cost of acquisition of seeds, and Total Cost of acquisition of fertilizers), the estimation of the econometric model required them to be transformed into logarithmic values.

RESULTS AND DISCUSSION

Stochastic frontier and technical inefficiency models

Given the specifications of the effects of technical

estimators for the parameters of the stochastic frontier inefficiency, Table 3 presents the maximum likelihood production function. According to the results obtained with the Wald Chi-square test, the model variables show a statistically significant association, that is, there is a relationship between the model variables. The absolute value Log Likelihood (1,552) is highly significant at the 99% confidence level. Therefore, the null hypothesis $H_0: 0$ (of no association between the model variables) is rejected. The estimated variance parameter γ (Gamma) is equal to 0.81, meaning that 81% of the total variance is expressed by the variance of technical inefficiencies.

The average technical efficiency (TE) was found to be 0.53, which indicates that in a scale of 0 to 100%, technical efficiency is 53% of the total efficiency⁴. This implies that on average agricultural households were producing 53% of the output that could potentially be produced with the observed input levels and their available technology. This is an interesting finding showing a deviation from the production possibilities frontier that is explained by the presence of technical inefficiency. Thus, technical inefficiency is 47% below the stochastic production frontier. This result is somehow different with other studies of technical efficiency. For instance, Seck (2016) found that farmers were producing 27.1% of the output they could produce, Dieng et al. (2019) found that Senegalese cashew nut farmers were producing 43% of the output that could potentially be producing with their observed input levels. While differences in estimations can be explained by various factors, such as sample size, composition of the sample and data features, both estimations exhibit lower coefficients of technical efficiency, indicating that there is room to improve agricultural output production by

³DAPSA calculated the sample size at a level of 7,755 agricultural households, spread over 1,460 physical census districts, at the rate of 5 households per census districts. This number came as 10% share of total count of 755,532 agricultural households practicing agriculture in Senegal as reported by the Recensement Général de la Population et de l'habitat, de l'agriculture et de l'élevage (RGPHAE). The agricultural survey covered all the regions of the country and all the departments, with the exception of Dakar, Pikine and Guédiawaye departments which were excluded from the scope of the survey due to the low level or even non-existence agricultural activity.

⁴ The standard deviation of technical efficiency was estimated to be 18%, which indicates that there was no significant variation between the inefficiency data of the estimated sample relative to the mean (data was not very dispersed).

Table 2. Structural variables and units of measurement.

Variable	Description	Unit of measurement	N
Yi	Gross value of production per agricultural HH	FCFA*	1,029
SUP	Total cultivated area	Hectare	1,029
MEC	Total cost of acquisition of machinery and equipment	FCFA	1,029
SEM	Total cost of acquiring seeds	FCFA	1,029
FERT	Total cost of acquiring fertilizers	FCFA	1,029
L1	Average number of days of family labor	Days	1,029
SEQ	Drought (proxy for climatic effects)	Dummy	1,029
FERT1	Use of fertilizers (1= applicable; 2= not applicable)	Dummy	1,029
SEM1	Use of certified/improved seed (1= use; 2= no use)	Dummy	1,029
MEC1	Use of machinery in agricultural activities (1= use; 2= no use)	Dummy	1,029
CAP	Specialized training of the household head (1= trained; 2= not trained)	Dummy	1,029
DPP	Property of the parcel (1= owned; 2= other)	Dummy	1,029

*FCFA = Franc Communauté Financière Africaine.

Source: Own elaboration based on microdata from AAS 2017/2018.

Table 3. Stochastic frontier normal/truncated-normal model.

Variable ^a	Coefficient	Std. Err.	Z	[95% Conf. Interval]	
Variance parameter					
Sigma2	3.617449	1.258206		1.829536	7.152598
Gamma	0.8102818	0.0667411		0.6458638	0.9091068
Sigma_u2	2.931153	1.253021		0.4752777	5.387029
Sigma_v2	0.686296	0.0683035		0.5524236	0.8201684
Log likelihood	-1,552				
Wald Chi ²	315.54	Prob > Chi ²	0.0000		
Mean technical efficiency					
TE	0.53	0.183725			
Variable ^b	Coefficient	Std. Err.	Z	P> z	[95% Conf. Interval]
Stochastic frontier model					
Cons.	5.032136	0.5177918	9.72***	0.000	4.0172826 0.046989
ISUP	0.1500441	0.0351701	4.27***	0.000	0.081112 0.2189762
IMEC	0.2215942	0.0340327	6.51***	0.000	0.1548912 0.2882971
ISEM	0.1184412	0.0289359	4.09***	0.000	0.0617279 0.1751545
IFERT	0.2717161	0.0272116	9.99***	0.000	0.2183823 0.3250499
IL1	-0.0471346	0.030025	-1.57	0.116	-0.1059824 0.0117133
Inefficiency model					
Cons	3.884594	1.485173	2.62	0.009	0.9737084 6.795479
SEQ	2.174152	0.848616	2.56**	0.010	0.5108949 3.837409
FERT1	-2.374465	0.9631411	-2.47**	0.014	-4,262,187 -0.4867431
SEM1	-0.6753234	0.5824083	-1.16	0.246	-1,816,823 0.4661758
MEC1	-0.2388473	0.1392226	-1.72*	0.086	-0.5117186 0.0340239
CAP	-0.8100593	0.5072245	-1.60	0.110	-1,804,201 0.1840825
DPP	-0.6603499	0.6021326	-1.10	0.273	-1,840,508 0.5198084

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

Source: Own elaboration based on microdata from AAS 2017/2018.

enhancing efficiency in the use of productive inputs. In practical terms, it is highly unlikely to find countries

where their farmers manage to reach their production possibilities frontier. Even the most advanced countries in

the globe are unable to achieve that frontier. For instance, a study for 15 countries of the European Union (EU-15) shows that the average technical efficiency was 87% in 2012 (Akande, 2012), implying that the EU-15 as a whole was producing 87% of the output that they could have produced with the available inputs and technology. Another study by Coelli and Rao (2005) found that technical efficiency for the EU-15 was 88%, while Rungsuriyawiboon and Lissitsa (2006) found a slightly lower technical efficiency coefficient (86%) for EU-15 region. Annexes 3 and 4 show the codes used in Stata 16 to estimate the Stochastic Frontier and the Technical Efficiency models.

Table 3 shows that the structural variables were converted into logarithms, which allowed their measurement in the form of input-output elasticities. The estimated β parameters (also known as product-frontier elasticities with respect to inputs or factors) are highly significant, except for family labor. The variable "area" ("ISUP") presents a positive elasticity of 0.15, meaning that an increase of 10% in cultivated areas implies a 1.5% increase in the Gross Value of Agricultural Production (Yi). The mechanization variable ("IMEC") presents a positive elasticity of 0.22, meaning that a 10% increase in the acquisition of machinery and equipment, generates a 2.2% increase in the Yi. Analogous reading can be given to seed ("ISEM") and fertilizer ("IFER") variables, which both present positive and statistically significant coefficients. Unlike the previous variables, the family labor ("IL1") variable presents a non-statistically significant negative elasticity of -0.047, meaning that an increase of 10% in family labor leads to a very small reduction of 0.47% in the Yi. In this case, it could be interpreted that family workforce needs knowledge enhancement in agricultural techniques, which could result in improvements in Yi.

In relation to the inefficiency parameters, a positive sign in the parameter increases technical inefficiency, while a negative sign reduces technical inefficiency. Drought ("SEQ") with a statistically significant coefficient of 2.17 has a positive sign indicating that the presence of drought increases technical inefficiency. This finding is very significant as it shows that drought is a fundamental factor of inefficiency in agricultural production in Senegal. This finding is consistent with other research (WB, 2015; USAID, 2014) which found that the most significant risk facing Senegalese agriculture is drought. Severe drought is the biggest risk in terms of aggregated losses coming from crop and livestock (WB, 2015). Increased drought frequencies due to climate change are likely to exacerbate the threat, particularly to rain-fed farmers (Pindiriri et al., 2016). As the percentage of the cultivated area equipped for irrigation is very low (3.7%, AQUASTAT, 2021), there is a strong dependency on rainfalls. When droughts strike, production and yields are very low. To reduce the drought effects, various measures could be considered such as introduction of water-saving technologies, improved irrigation methods,

cultivation of crops that use minimum water resources, and/or development of drought-resistant crop varieties.

Fertilizers ("FERT1") has a statistically significant negative coefficient (-2.37) indicating that low use of fertilizers is a source of agricultural inefficiency, and that additional and more efficient use of fertilizers would lead to higher efficiency. Backing up this finding, data from the 2019-2020 Rapport de la phase 1 de l'Enquête Agricole Annuelle (EAA) indicates that just 31% of agricultural households use mineral fertilizers (DAPSA, 2020) in the form of NPK, urea and phosphate. Moreover, the use of these fertilizers is below the recommended doses. For example, in the case of NPK, maize uses 78% of the recommended dose, millet 77%, peanut 71%, rainfed rice 86%, sorghum 69%, and watermelon 62% (DAPSA, 2020). Furthermore, these fertilizers were largely acquired through subsidies provided by the government⁵. That is, 46% of agricultural parcels cultivated with maize used subsidized NPK, 61% in the case of millet, 62% in the case of peanut, 11% in the case of rainfed rice, 20% in the case of sorghum, and 69% in the case of watermelon (DAPSA, 2020). At regional level, fertilizer consumption (measured in kilograms per hectare of arable land) in 2018 Senegal ranked eight among ten selected African countries, displaying a relatively low consumption of nutrients per hectare of arable land⁶.

Mechanization ("MEC1") has a statistically significant negative coefficient (-0.24) indicating that lack of mechanization is a source of agricultural inefficiency, and that additional and more efficient use of machinery and equipment in production processes would lead to higher efficiency. Backing up this finding, the 2014-2017 "Programme d'accélération de la Cadence de l'agriculture Senegalese" (PRACAS) reported that just 5% of farms count with mechanize cultivation equipment (Ministry of Agriculture, 2014). More recently, the 2020-2021 Rapport de l'Enquête Agricole Annuelle (EAA) showed that in 2020 just 3.3% of all agricultural plots in the country used motorized equipment (DAPSA, 2021). To modernize agriculture and improve productivity, in 2018 the government distributed, through the "Programme National d'Investissement Agricole pour la Sécurité Alimentaire et la Nutrition" (PNIASAN), 1,000 tractors aiming at intensifying agricultural mechanization in more than 30,000 ha (Focus Guinee, 2019). These investments are expected to increase productivity and promote the well-being of agricultural populations and rural households.

While the coefficients of certified/improved seed use, training of household heads, and parcel property are not

⁵Since 2011, the Senegalese government implemented a subsidy programme that consisted of facilitating farmers' access to fertilizers at subsidized prices (IFPRI, 2016).

⁶Source: WDI, 2022. Data on fertilizer consumption (in kilograms per hectare of arable land): South Africa (72.8), Zambia (52.5), Zimbabwe (38.4), Ethiopia (36.2), Ghana (29.4), Namibia (27.3), Burundi (23.8), Senegal (22.3), Nigeria (19.7), and Burkina Faso (17.6). <https://databank.worldbank.org/source/world-development-indicators>.

Table 4. Returns to scale.

Variable	Elasticity
ISUP	0.154***
IMEC	0.222***
ISEM	0.118***
IFERT	0.272***
IL1	-0.047
Sum	0.72

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

Source: Own elaboration based on microdata from AAS 2017/2018.

statistically significant, they all have all expected signs (-0.67, -0.81 and -0.66 respectively). These results suggest that in principle augmenting their use reduces technical inefficiency. Yet, the fact that these coefficients are not statistically significant suggests that further research is needed to determine the extent to which technical inefficiency reduces when augmenting their use.

A limitation of the study was to control the primary information contained in the survey. That is, some outlier observations were eliminated because those were data values that lied at the tails of statistical distributions, and thus were likely to be incorrect data.

Returns to scale

Returns to scale, calculated as the sum of output elasticities for all inputs, was estimated to be 0.72, indicating that on average agricultural production in Senegal has diminishing returns to scale, that is, if farmers increase all factors of production by 10%, the total value of agricultural production would increase in average by 7.2%.

Technical efficiency by region

Previously, it was shown that the average technical efficiency (TE) was found to be 0.53 at national level. Technical efficiency can also be analyzed by region, which allows identifying the most and least efficient regions and, thus, outlining policy guidelines based on geographical indications. To this end, the sample size of 1,029 households was broken down according to all 14 regions of the country. Table 5 shows the number of households per region.

Tambacounda was found to be the most technically efficient region of the country (coefficient of 0.64 in a scale 0 to 1), implying that farmers in this region produced on average 64% of the output that they could potentially produce with the observed input levels and observed available technology. This value shows that in relative terms, in this region agricultural producers are the most efficient compared with the rest as they make better

use and/or combination of factors in the agricultural production process (Table 4). Kedougou region was found to be the least efficient region of the country (coefficient of 0.34). This value suggests that producers of this region obtain in average 34% of the output they could potentially produce if available inputs and technology would be utilized to their maximum production capability.

Seven regions (Tambacounda, Fatick, Sedhiou, Kaffrine, Louga, Kolda and Kaolack) were found to be above or equal to the national average of technical efficiency, meaning that these regions make more appropriate use and/or combination of factors in the production process. Another seven (Diourbel, Dakar, Ziguinchor, Saint-Lois, Matam, Thies and Kedougou) were below the national average of technical efficiency, implying that generally the combination of production factors were the least efficient at their current technology available. Further studies would be needed to determine the underlying factors leading to inefficiency in each region. At national level it was identified that drought is a significant explanatory factor impacting negatively on technical efficiency.

Conclusion

The main finding of this paper showed that on average agricultural households produced 53% of the output that they could have produced with the observed input levels and technology available. This implies that their level of production was below the production frontier, achievable when farmers are able to transform their available inputs into a maximum attainable output given the available technology.

Inefficiency is associated to vulnerability to droughts, insufficient use of fertilizers, and low mechanization used in agricultural production. Drought is a major factor of inefficiency in agricultural production in Senegal. To minimize its effects, various policy options could be promoted such as improved irrigation programmes particularly in drought-prone areas, shifting to crops that use minimum water resources, and promoting the use of drought-resistant crop varieties, which all could lead to improvements in technical efficiency.

There is also great potential to improve technical efficiency through greater use of fertilizers. The government of Senegal is aware of insufficient use of fertilizers in the country. Subsidy mechanisms implemented since 2011 seem to be helping to promote fertilizer use, but subsidies can be difficult to maintain in the long run. Other market-oriented incentives should be explored⁷, which could result in improved soil nutrition

⁷Which go beyond the purpose of this research but are well-documented in pertinent literature, and include reducing transaction cost, eliminating import tariffs to fertilizers, and promoting market-oriented allocation of production resources.

Table 5. Technical efficiency by region.

1	Tambacounda	108	0.64	0.12	0.10	0.80
2	Fatick	55	0.60	0.99	0.31	0.77
3	Sedhiou	44	0.58	0.21	0.07	0.81
4	Kaffrine	117	0.58	0.16	0.00	0.80
5	Louga	39	0.58	0.16	0.22	0.84
6	Kolda	125	0.58	0.15	0.06	0.88
7	Kaolack	241	0.53	0.16	0.04	0.83
8	Diourbel	59	0.51	0.17	0.09	0.80
9	Dakar	5	0.51	0.13	0.40	0.71
10	Ziguinchor	11	0.46	0.18	0.22	0.72
11	Saint-Louis	43	0.46	0.21	0.07	0.83
12	Matam	25	0.43	0.20	0.03	0.73
13	Thies	20	0.39	0.15	0.15	0.64
14	Kedougou	137	0.34	0.17	0.01	0.70
Total		1,029				
National average			0.53	0.18		

Source: Own elaboration based on microdata from AAS 2017/2018.

coming from more and more efficient use of fertilizers prompting to higher yields and more efficient production processes.

The government and private sector should motivate farmers to increase the use of agricultural machineries to improve agricultural production. This should enhance soil preparation, should lower tillage costs, and result in higher yields and greater efficiency. Training of household heads is a driver of technical efficiency, whose improvement should be promoted and accompanied by programs of technical assistance, which should result in enhanced family labor and improved gross value of agricultural production.

All the regions of the agricultural sector in Senegal are below the production frontier, which implies that the productive units located in each of them are not maximizing the use of their inputs or productive factors. The Tambacounda region is the most efficient, while the Kedougou region is the less efficient. While more studies are needed to determine region-specific drivers of technical efficiency, identifying which are the most and the least efficient regions sheds some light of the efforts needed to enhance technical efficiency.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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ANNEXES

Annex 1: Lineal model

glm IY ISUP IMEC ISEM IFERT IL1

```

Iteration 0: log likelihood = -1605.8138

Generalized linear models          Number of obs =    1,029
Optimization      : ML              Residual df   =    1,023
                                          Scale parameter =  1.335207
Deviance          =  1365.916476      (1/df) Deviance =  1.335207
Pearson          =  1365.916476      (1/df) Pearson  =  1.335207

Variance function: V(u) = 1          [Gaussian]
Link function     : g(u) = u         [Identity]

                                          AIC           =   3.132777
                                          BIC           =  -5729.962

Log likelihood    = -1605.813783
    
```

IY	OIM			P> z	[95% Conf. Interval]	
	Coef.	Std. Err.	z			
ISUP	.1183374	.0389179	3.04	0.002	.0420597	.194615
IMEC	.325189	.0312171	10.42	0.000	.2640045	.3863734
ISEM	.1551049	.0295468	5.25	0.000	.0971943	.2130156
IFERT	.2512719	.0294577	8.53	0.000	.1935359	.3090079
IL1	-.0972865	.0325328	-2.99	0.003	-.1610495	-.0335234
_cons	3.31596	.4887731	6.78	0.000	2.357982	4.273938

Annex 2: Hypothesis Testing

For this model, the null hypothesis is tested as follows: there are no technical inefficiency effects and therefore the parameters can be estimated using ordinary least squares (OLS), with the alternative hypothesis: there are inefficiency effects and therefore the estimators cannot be calculated using OLS, but by Maximum Likelihood.

Therefore:

$$H_0: \gamma = 0$$

$$H_1: \gamma > 0$$

To test the H_0 , the value of the LR Statistic must be compared with the combined Chi-square table value (Kodde and Palm, 1986) with a number of restrictions equal to six⁸, rejecting the H_0 if the value of the LR statistic is greater than the table value.

The LR statistic is calculated as:

$$LR = -2[\ln\{L(H_0)\} - \ln\{L(H_1)\}]$$

$$LR = -2[(-1605,813783) - (-1551.9711)]$$

$$LR = 107.69$$

As the value of LR (107.69) is greater than the value of the combined Chi-square table⁹, the $H_0: \gamma = 0$ is rejected in favor of $H_1: \gamma > 0$ at 99% significance.

⁸Corresponds to the number of parameters of the technical efficiency model.
⁹The values of the combined Chi-square table (Kodde and Palm, 1986) are as follows:

Degrees of freedom	$\alpha = 0.1$	$\alpha = 0.05$	$\alpha = 0.01$
6	10.6446	12.5916	16.8119

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

Annex 3: Stochastic Frontier Model

Frontier IY ISUP IMEC ISEM IFERT IL1, dist(tnormal) cm(SEQ FERT1 SEM1 MEC1 CAP DPP)

Stoc. frontier normal/truncated-normal model Number of obs = **1,029**
 Wald chi2(5) = **315.54**
 Log likelihood = -1551.9711 Prob > chi2 = **0.0000**

	IY	Coef.	Std. Err.	z	P> z	[95% Conf. Interval]	
IY							
	ISUP	.1500441	.0351701	4.27	0.000	.081112	.2189762
	IMEC	.2215942	.0340327	6.51	0.000	.1548912	.2882971
	ISEM	.1184412	.0289359	4.09	0.000	.0617279	.1751545
	IFERT	.2717161	.0272116	9.99	0.000	.2183823	.3250499
	IL1	-.0471346	.030025	-1.57	0.116	-.1059824	.0117133
	_cons	5.032136	.5177918	9.72	0.000	4.017282	6.046989
mu							
	SEQ	2.174152	.848616	2.56	0.010	.5108949	3.837409
	FERT1	-2.374465	.9631411	-2.47	0.014	-4.262187	-.4867431
	SEM1	-.6753234	.5824083	-1.16	0.246	-1.816823	.4661758
	MEC1	-.2388473	.1392226	-1.72	0.086	-.5117186	.0340239
	CAP	-.8100593	.5072245	-1.60	0.110	-1.804201	.1840825
	DPP	-.6603499	.6021326	-1.10	0.273	-1.840508	.5198084
	_cons	3.884594	1.485173	2.62	0.009	.9737084	6.795479
	/lnsigma2	1.285769	.3478159	3.70	0.000	.6040626	1.967476
	/lgtgamma	1.451842	.4341585	3.34	0.001	.6009071	2.302777
	sigma2	3.617449	1.258206			1.829536	7.152598
	gamma	.8102818	.0667411			.6458638	.9091068
	sigma_u2	2.931153	1.253021			.4752777	5.387029
	sigma_v2	.686296	.0683035			.5524236	.8201684

Annex 4: Technical efficiency

tabstat te1, statistics(mean sd min max) by(Región)

Summary for variables: te1
by categories of: Región (Región)

Región	mean	sd	min	max
1	.5086726	.1304374	.40142	.713111
2	.4627551	.1801978	.2248499	.7155911
3	.5134212	.1693763	.0932669	.8038666
4	.4562118	.205938	.0725698	.8345568
5	.6353363	.1207919	.1026959	.7987237
6	.5300097	.1630299	.0366471	.8260565
7	.3925825	.1456297	.1515356	.6407456
8	.5784865	.1629064	.2158256	.837736
9	.6039271	.0992837	.3077119	.7747284
10	.5773432	.148857	.0629034	.8837337
11	.4320931	.2037992	.0333842	.7333514
12	.5810038	.1613366	.0045789	.798219
13	.3390355	.1731718	.014711	.7003593
14	.583117	.2125832	.0651366	.8146444
Total	.5253378	.1837248	.0045789	.8837337

¹Sample size of 1,029 households were selected based on the number of cases that had information about specific variables of interest, such as fertilizers, certified seeds, irrigation, mechanization, pesticides, training of the household head, and property of the parcel.