Technical efficiency and production potential of selected cereal crops in Senegal

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Abstract

This study focused on the production outcomes for five crops cultivated in Senegal: upland rice, lowland rice, groundnut, maize, and pearl millet. Technical efficiency (TE) of the production of each crop was estimated using data envelopment analysis, and the determinants of TEs were assessed using generalised linear regression analyses. Data were collected in face-to-face interviews with 66 farmers in the Kaolack region of Central Senegal during November 2011–February 2012. Average TEs for upland rice, lowland rice, groundnut, maize, and pearl millet were estimated as 0.76, 0.88, 0.89, 0.94, and 0.90, respectively. The identified factors that had a positive impact on TE were years of cultivation experience, amount of nitrogen fertiliser applied, and participation in a farmers' association. Weeding hours, seeding rate, size of the cultivated area, and delays in sowing time were negatively associated with TE. The factors that significantly affected TE differed among the crops. Optimising these factors could enable potential yield increase of upland rice, lowland rice, groundnut, maize, and pearl millet by 24, 12, 11, 6, and 10 %, respectively.

Keywords: production function, agricultural extension, data envelopment analysis (DEA), rice, West Africa

1 Introduction

More than 54 % of Senegalese people live in rural areas (ANSD, 2014), and almost 25 % of these are estimated to suffer from malnutrition (FAO *et al.*, 2015). Based on the estimation that the national population will reach 23 million in 2030 (UN, 2015), the number of malnourished people is expected to increase to more than 3 million by 2030. Therefore, the Senegal government put high priority to increase agricultural productivity (FAO, 2015; IMF, 2013).

The main crops cultivated in Senegal are rice, groundnut, maize, and pearl millet. Rice is one of the most important crops with an annual consumption per capita of 91 kg in 2014/2015 (USDA, 2015). However, Senegal produces only 20–30 % of the total consumed rice (USDA, 2015). To improve the production, the Senegal government has set a national goal to produce 1.6 million t in 2017. Although this is a challenging target as production in 2015 was only 623,000 t (USDA, 2016), it is important for Senegal to achieve this goal because the price of imported rice is very volatile and large price variations make the livelihoods of Senegalese people unstable.

Crop yield can be increased in two ways: expanding the cultivated area and/or increasing the yield per unit of harvested area. Expanding the area under cultivation is almost not feasible in Senegal as the available uplands are being cropped already. Competition for uplands is very intense, and according to our interviews, almost all the surveyed farmers cultivate their uplands continuously, without a sufficient fallow period (Grosenick *et al.*, 1990; Diop, 1999). Furthermore, labour shortages

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restrict expansion of the lowlands. This labour shortage is related to climatic conditions, as the demand for farming labourers is largely restricted to the four months rainy period. As there are few employment opportunities in rural areas during dry season, people tend to migrate to urban areas or overseas to look for jobs. Once people have moved away from rural areas, they are unlikely to return home and tend to stay in their new location to maintain employment. Consequently, only 37 % of the potentially cultivable lowland area is in use for crop production in Senegal (Frenken, 2005).

Per-area yield can be improved by optimising farming (i.e. sowing, fertiliser application, or weeding), which requires little additional cost. Increasing the amount and quality of production inputs will increase the per-area yield as well. However, the purchase of inputs as chemical fertiliser or high quality seeds is restricted as Senegalese farmers do not have adequate financial resources and their access to financial services is limited (AFAP & IFDC, 2014). Therefore, an effective option to increase yield may be to adjust and optimise current farming practices.

The concept of technical efficiency (TE) is very useful for comparing levels of production efficiency, and TE can be used to identify the factors to improve the productivity of a decision-making unit (e.g. farm). Moreover, TE is useful to evaluate the disparity of technical level between individual farmers for each crop. This can be helpful to identify higher priority crops or farmers requiring technical support. Therefore, many studies have investigated the TE of farms in West Africa, but only three studies have been conducted in Senegal so far (see Table 4).

In the present study, we estimated TEs for five selected crops that are cultivated widely in Senegal: upland rice, lowland rice, groundnut, maize, and pearl millet. We examined the main factors influencing TE using a regression analysis with a generalised linear model. Our analyses indicated the change in farming practices required to improve crop yield. These findings will be helpful for extension programmes targeting resource poor farmers to increase their crop productivity.

2 Materials and methods

2.1 Study area and data collection

The study area was the Médina Sabakh community, located at 13°36′ N 15°35′ W in the Kaolack region, Central Senegal. This community had 34,263 persons living in 4,104 households in 2014–2015 (data from the local authority). There are two seasons: a rainy season from the end of June to the middle of October; and a dry season from the end of October to the middle of June. Rainfall occurs only during the rainy season, and the average annual precipitation is 766 mm (1988–2014, data from the Ministry of Agriculture in Senegal). A preliminary survey revealed that farmers usually cultivate rice, groundnut, maize, or pearl millet during the rainy season. Groundnut is cultivated as the main cash crop, and the other crops are mainly grown for personal consumption.

The survey was conducted from 27 November 2011 to 12 February 2012 through face-to-face interviews using structured questionnaires. The farmers included in the survey were selected randomly from all farms that cultivated rice in 2010 in the Médina Sabakh community, according to our preliminary survey. In total, 66 farmers were interviewed about the crops cultivated during the rainy seasons from 2009 to 2011 (upland rice, lowland rice, groundnut, maize, or pearl millet). The average number of crops cultivated was 2.3 per farm. The number of valid responses was 33 for upland rice, 19 for lowland rice, 38 for groundnut, 29 for maize, and 36 for pearl millet.

The items identified for the survey were age of the head of the household, number of family members working on the farm, cultivated area of the respective crops (ha), yield of each individual crop (t ha^{-1}), amount of nitrogen fertiliser applied (kg-N ha^{-1}), seeding rate (kg ha^{-1}), number of hours spent weeding (person h ha^{-1}), years of experience cultivating the particular crops (years), seeding sequence of crops on the farm, and experience of participating in a farmers' association. Data on yield and production inputs were based on the largest field of each crop cultivated by each farmer.

The amount of nitrogen applied was estimated by multiplying the weight of chemical fertiliser and animal manure by the amounts of nitrogen in these substances. The farmers provided the figure for the amount of nitrogen in the chemical fertiliser (6–15 %) and the amount of nitrogen in animal manure was set at 2.6 % as reported by Pratt & Castellanos (1981).

The time spent weeding (total weeding hours per ha) was used as a measure of total labour input. The weeding hours per ha were calculated from the time spent on inter-tillage weeding with animal traction hoes plus the time spent on manual weeding with hand hoes. Labour inputs from other farming practices, such as scaring away birds or applying fertilisers, were not included in the analysis for the following reasons. First, although

scaring birds is a common and labour-intensive activity in rice and pearl millet farming in Africa, the farmers in the sample area did not follow this practise. Instead, they try to minimise bird damage by synchronising the maturation and harvest periods of rice and pearl millet. When synchronisation fails, the maturation and harvesting periods extend and damages from bird increase. Second, the amount of labour involved in fertiliser application is relatively low. Le Moigne (1980) estimated that labour input for fertiliser application was the equivalent of only 2–6 % of the total labour input in Senegal. In addition, our preliminary survey indicated that the labour input for fertiliser application was perfectly correlated with the amount of the fertiliser applied (unpublished).

The years of cultivation-experience possessed by the head of the farm household was included only in the analysis of upland and lowland rice production because we could not obtain reliable data for the other crops. The head of the household had cultivated crops other than rice from their youth on; the years of cultivation experience were closely related to their ages.

2.2 Analytical framework

2.2.1 Technical background

TE is an indicator that is defined as the ratio of a measured production level to the potential production level with given level of inputs and production technology (Farrell, 1957; Coelli *et al.*, 2005). The potential production level is on the frontier production function estimated as an envelopment surface of observed production data (Coelli *et al.*, 2005). Thus, a perfectly efficient farm has TE = 1, whereas an inefficient farm has $0 \leq \text{TE} < 1$. The value $1 - \text{TE}$ indicates the inefficiency level of a farm.

The frontier production function and TE can be estimated by two different approaches: a non-parametric approach, such as data envelopment analysis (DEA), or a parametric approach, such as stochastic frontier analysis (SFA). TE estimation by DEA is appropriate when the distribution of TE is not known *a priori*, and has an advantage in terms of identifying efficient farmers, who can act as role models for inefficient farmers. Therefore, DEA is applied in this analysis.

2.2.2 Data envelopment analysis

DEA has two calculation models: the variable returns to scale (VRS) model and the constant returns to scale (CRS) with an input-orientation or an output-orientation. In the survey area, as scale merits in cereal productions do not exist (Kelly *et al.*, 1996),

CRS model is employed. Although an input-oriented or an output-oriented assumption is selected based on a purpose to measure TE by a proportional reduction in input usage or a proportional increase in output production, the two measuring methods provide the same value of TE under CRS model (Coelli, 1996). The input-oriented CRS DEA model applied in this study is specified as:

$$\min_{\theta_{im}, \lambda_{i1} \cdots \lambda_{in_i}} \theta,$$

subject to

$$-y_{im} + \sum_{j=1}^{n_i} y_{ij}\lambda_{ij} \geq 0,$$

$$\theta x_{kim} - \sum_{j=1}^{n_i} x_{kij}\lambda_{ij} \geq 0,$$

$$\lambda_{ij} \geq 0, i = 1, 2, \ldots, 5; j = 1, \ldots, m, \ldots, n_i; k = 1, 2, 3$$

where θ is TE of the ith crop of the jth farmer, y_{im} is the output of the ith crop of an observed farmer, λ_{ij} denotes weights which define the linear combination of the peer of the ith crop of the jth farmer, x_{kim} is the kth input of the ith crop of an observed farmer, and x_{kij} is the kth input of the ith crop of the jth farmer. Estimation is carried out by using the program DEAP version 2.1.

2.2.3 TE distribution

A crop having low TE has large potential of increasing production and therefore high priority in terms of agricultural extension. In order to decide the priority of crops, an average TE of each crop was estimated and the mean difference was tested by the Tukey-Kramer method. Furthermore, the TE distribution of each crop was compared using the kernel density distribution, which was calculated using Analytical Methods Committee software with a Gaussian kernel and a bandwidth h where,

$$h = 0.9 \times \min(\text{sample standard deviation}, \text{IQR}/1.34) \times n^{-1/5}$$

where IQR denotes the inter-quartile range of the data.

2.2.4 Determinant analysis of TE

We identified TE determinants through regression analyses. Since the dependent variable, TE, is bound within the range 0–1, it was not appropriate to use an ordinary least square method. Therefore, we applied a generalised linear model with logit link function:

$$\ln\left(\frac{\text{TE}_i}{1 - \text{TE}_i}\right) = \beta_{i0} + \sum_{l=1}^{7} \beta_{il}X_{il} + w_i$$

where TE_i is estimated technical efficiency of i th crop, X_{il} represents l th explanatory variable of the i th crop, β_{il} is unknown parameters to be estimated, and w_i is the error term. $t\,ha^{-1}$ To estimate the TE, amount of nitrogen applied (kg-$N\,ha^{-1}$), seeding rate ($kg\,ha^{-1}$), and weeding hours (person $h\,ha^{-1}$) were used as inputs; the yield per cultivated area ($t\,ha^{-1}$) was used as the output variable. Possible crop variety effects were not accounted for.

3   Results

3.1   Descriptive statistics

The basic data collected are presented in Table 1. Lowland rice had the highest yield ($1.5\,t\,ha^{-1}$), followed by maize ($1.0\,t\,ha^{-1}$) and the other crops (0.59–$0.73\,t\,ha^{-1}$). Nitrogen was intensively applied for upland rice and maize (72–$74\,kg\,ha^{-1}$), and it was mainly derived from chemical fertiliser. The seeding rate for groundnut ($71\,kg\,ha^{-1}$) was the highest, followed by upland rice, lowland rice, and maize (18–$28\,kg\,ha^{-1}$). The seeds of all plants were directly sown with a seeder pulled by draft animal. More hours were spent weeding in upland rice and lowland rice than in the other crops. The cultivated areas of groundnut and pearl millet were the highest among the crops. Years of cultivation experience were 2.51 and 3.81 for upland rice and lowland rice, respectively.

3.2   TEs and their distributions

The TEs obtained for the five crops are shown in Table 2. The average TEs of upland rice, lowland rice, groundnut, maize, and pearl millet were 0.76, 0.88, 0.89, 0.94, and 0.90, respectively. From these results, crop yields may be potentially increased in the range of 6 % (maize) to 24 % (upland rice). The TE for upland rice was significantly lower than those for the other crops.

The TE distributions for upland and lowland rice have two peaks (Fig. 1a, b). The peaks in upland rice appear at 0.5 and 0.8 and the distribution has a long tail. In contrast, the peaks in lowland rice appear between 0.8 and 1.0 and the variation is small. The distributions of the other crops have a single peak at 0.9 (Fig. 1c, d, e). The pooled TEs of all five crops had a single peak at 0.9 (Fig. 1f).
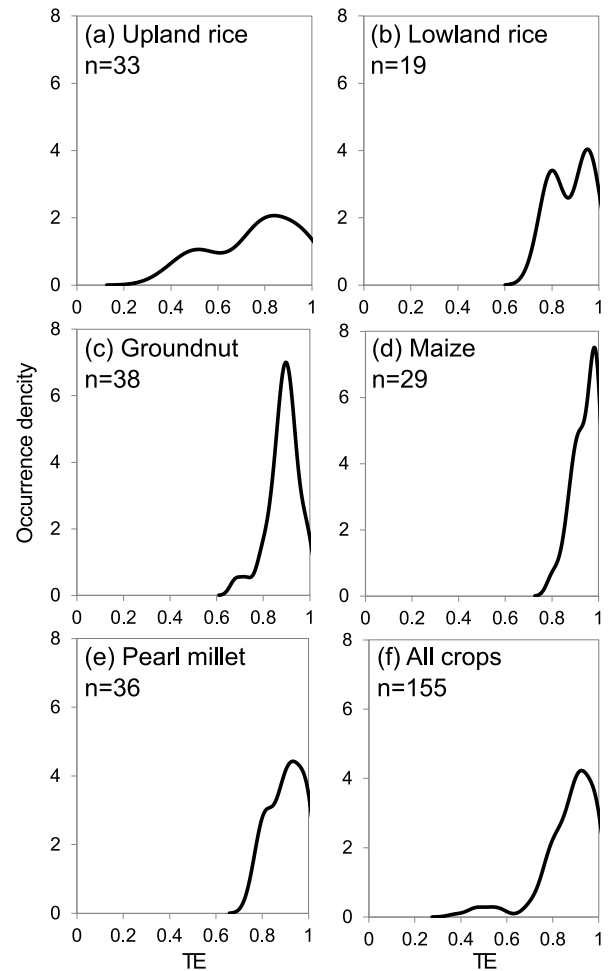

Fig. 1: *Distribution of technical efficiency (TE) estimated by kernel density in selected crops (**a–e**), and for all crops (**f**).*

3.3   Determinants of TE

Variables that might contribute to TE were examined using generalised linear regression analyses (Table 3). A significant positive factor affecting the TE of upland rice was year of cultivation experience ($P < 0.01$), whereas a significant negative factor was delay in sowing time ($P < 0.01$). For lowland rice, year of cultivation experience ($P < 0.01$) and participation in a farmers' association ($P < 0.05$) were positive factors, while weeding hours ($P < 0.01$), seeding rate ($P < 0.01$), cultivated land area ($P < 0.01$) and delay in sowing time ($P < 0.05$) were significant negative factors. For groundnut, the amount of nitrogen applied ($P < 0.05$) was a significant positive factor, while weeding hours ($P < 0.01$) and delay in sowing time ($P < 0.05$) were significant negative factors. For pearl millet, a significant positive factor was the amount of nitrogen applied ($P < 0.05$), while significant negative factors were weeding hours ($P < 0.05$) and seeding rate ($P < 0.01$). No significant variables were identified for maize production.

Table 1: *Basic statistics of the sample (average over the years 2009–2011).*

Categories	Variables	Upland rice	Lowland rice	Groundnut	Maize	Pearl millet
Output	Yield (t ha^{-1})	0.64 [0.55] [a]	1.5 [0.81] [c]	0.73 [0.31] [ab]	1.0 [0.54] [b]	0.59 [0.33] [a]
Inputs	Fertiliser (kg-N ha^{-1})	74 [49] [b]	16 [24] [a]	1.5 [2.9] [a]	72 [32] [b]	19 [17] [a]
	⟨% of N derived from chemical fertiliser⟩	⟨86⟩	⟨80⟩	⟨57⟩	⟨91⟩	⟨79⟩
	Seed (kg ha^{-1})	26 [16] [b]	28 [19] [b]	71 [26] [c]	18 [6.6] [b]	4.9 [2.8] [a]
	Weeding (h ha^{-1})	470 [230] [b]	430 [130] [b]	150 [57] [a]	150 [72] [a]	120 [39] [a]
Characteristics	Plot area (ha)	0.53 [0.33] [a]	0.61 [0.57] [a]	2.8 [2.1] [b]	1.3 [0.80] [a]	2.8 [1.5] [b]
	Cultivation experience (years)	2.51 [1.15] [a]	3.84 [2.14] [b]	n.a.	n.a.	n.a.
	Age (years)	54 [9.7] [a]	52 [10] [a]	52 [11] [a]	54 [11] [a]	52 [11] [a]
	No. family labourers (persons)	12 [7.2] [a]	14 [21] [a]	15 [17] [a]	15 [17] [a]	14 [16] [a]
Sample size		33	19	38	29	36
Share of the farmers (%)		50	29	58	44	55

[a,b,c] Means with a different superscript are significantly different (*P* < 0.05), Standard deviation in brackets; n.a. not applicable.

Table 2: *Summary statistics of technical efficiency.*

	Upland rice	Lowland rice	Groundnut	Maize	Pearl millet	Total
Mean	0.76 [a]	0.88 [b]	0.89 [b]	0.94 [b]	0.90 [b]	0.87
Std Dev.	0.19	0.09	0.07	0.05	0.07	0.12
Min	0.38	0.73	0.68	0.80	0.76	0.38
Max	1.00	1.00	1.00	1.00	1.00	1.00
Sample size	33	19	38	29	36	155

[a,b,c] Means with a different superscript are significantly different (*P* < 0.05)

Table 3: *Determinants of technical efficiency.*

	Upland rice	Lowland rice	Groundnut	Pearl millet
ln (Weeding hours)	n.s.	−1.65 ** [−5.04]	−1.10 ** [−3.26]	−0.73 * [−2.47]
ln (Amount nitrogen applied)	n.s.	n.s.	0.42 * [2.44]	0.24 * [2.35]
ln (Seeding rate)	n.s.	−0.93 ** [−2.57]	n.s.	−0.70 ** [−2.73]
ln (Years of cultivation experience)	1.04 ** [3.72]	1.25 ** [4.67]	n.a.	n.a.
ln (Cultivated area)	n.s.	−1.10 ** [−5.17]	n.s.	n.s.
Delayed sowing time (Dummy)	−0.74 ** [−2.57]	−0.50 * [−2.09]	−0.37 * [−2.37]	n.s.
Participation in a farmers' association (Dummy)	n.s.	0.85 * [2.36]	n.s.	n.s.
Constant	0.70 * [2.49]	12.6 ** [6.20]	7.46 ** [4.46]	6.16 ** [4.66]
n	33	19	38	36
AIC	−36	−56	−104	−93
BIC	−32	−49	−97	−87

* *P* < 0.05; ** *P* < 0.01; *t*-values in parenthesis;
AIC: Akaike's Information Criterion; BIC: Bayesian Information Criterion.

4　Discussion

4.1　Production output and inputs

The average yield of upland rice and lowland rice were 0.64 and 1.5 t ha^{-1}, respectively. These yields are considerably lower than the national averages of 3.92 t ha^{-1} (FAO Stat, 2009–2014), perhaps because rice crops in the study area were cultivated rainfed, whereas irrigation is widely used elsewhere. However, the estimated yield of 1.5 t ha^{-1} for lowland rice is equivalent to that reported for rainfed rice in West and Central Africa (Nin-Pratt et al., 2011). The estimated yields for groundnut, maize, and pearl millet were comparable with the national yield averages, 0.85, 1.41, and 0.70 t ha^{-1}, respectively (FAO Stat, 2009–2014), as well as with the regional averages for West and Central Africa, 0.83, 1.24, and 0.72 t ha^{-1}, respectively (Nin-Pratt et al., 2011).

The recommended amounts of nitrogen application for upland rice, lowland rice, groundnut, maize, and pearl millet were 61–99 kg-N ha^{-1} (Akintayo et al., 2008; Ekeleme et al., 2008), 76–99 kg-N ha^{-1} (Ekeleme et al., 2008), 25 kg-N ha^{-1} (Ajeigbe et al., 2014), 40–120 kg-N ha^{-1} (Belfield & Brown, 2008; Sommer et al., 2013), and 20–60 kg-N ha^{-1} (Khairwal et al., 2007), respectively. Compared to these recommended amounts, the amounts applied to lowland rice (16 kg-N ha^{-1}) and groundnut (1.5 kg-N ha^{-1}) in this study were low. The comparatively small amount of nitrogen applied for lowland rice production is a consequence of the relatively high soil fertility. Fields used for lowland rice production are generally fertile because these are recently taken under cultivation and these receive nutrients from upland areas. In the case of groundnut, farmers are aware of the nitrogen-fixing capacity of groundnut so N application is low. For the other crops, access to subsidies for fertiliser (Druilhe & Barreiro-Hurlé, 2012) or to in-kind payment loans (farmers can receive chemical fertilisers at the beginning of the cultivation season without payment and then pay back the cost of the fertilisers in form of the harvested crop) provided by local NGOs contribute to appropriate application levels of nitrogen fertiliser.

Recommended seeding rates for upland rice, lowland rice, groundnut, maize, and pearl millet in Senegal or other West African countries are 40–60, 50–60, 60–66, 20, and 3.5–5.0 kg ha^{-1}, respectively (Havard, 1986; Freud et al., 1997; Akintayo et al., 2008; Ekeleme et al., 2008; Ragasa et al., 2013). The rates in the surveyed area for groundnut and maize were consistent with the recommended levels whereas that of pearl millet was slightly higher, and the rates of upland and lowland rice were at approximately 25–50 % of the recommended levels. These differences reflect variations in sowing methods in Senegal compared to other West African countries. Single row seeder (general type) is very in common use for Senegalese than Malian or Nigerian (Le Moigne, 1980; Schmitz et al., 1991). As a result, drilling has been adopted as the conventional sowing method in Senegal while in the countries where the availability of seeders is low, the crops are sown broadcast or by dibbling (making small holes and sowing seeds in the holes).

Weeding time spent on rice was 2.8–3.9 times longer than for the other crops. For upland rice the weeding time was 1.2–2.3 times longer than found in other West African countries (Dalton et al., 1998). This increased weeding effort in rice cultivation may be due to inefficient weed management arising from a relatively low cultivation experience (Linares, 2002), or due to a higher motivation for intensive management because of a higher market value or a higher consumption demand.

Each farmer devoted ca. 70 % of the cultivated land to groundnut and pearl millet (approximately 2.8 ha each; Table 1). This reflects the fact that groundnut is the main cash crop and pearl millet is the traditional staple crop. In contrast, the area devoted to rice and maize was approximately one-quarter to one-half of that devoted to groundnut and pearl millet. Rice and maize do not only require more inputs (e.g. fertiliser), these crops are also not as drought resistant as groundnut and pearl millet. Therefore, under the existing rainfed conditions it is a challenge for Senegalese farmers to expand the areas under rice and maize cultivation.

4.2　TEs and their distributions

The TE of upland rice was lower and more variable than that of other crops (Table 2). This reflects that farmers tend to easily start growing upland rice but the cultivation techniques are in fact difficult; the yield of upland rice is far more affected by farming practices or environmental conditions such as the amount and distribution of rainfall. Consequently, the TE in upland rice was relatively low and very variable (Fig. 1). The higher TE and lower variation found in lowland rice are the result of higher soil fertility and water availability. Furthermore, as the farmers have to invest in the development of lowland fields for planting rice, this act as a barrier for farmers with severe resource constraints. The initial investments are also an incentive for farmers to achieve a high yield to recover the cost as soon as possible. The lowland rice TE peaks at 0.8 and 0.9 (Fig. 1) suggest that two different environments, that accompany the distance

Y. Okuyama et al. / J. Agr. Rural Develop. Trop. Subtrop. 118 - 2 (2017) 187–197

193

from Gambia, coexist among the lowland rice farmers. The study area included land at the national border with Gambia (a country where people have long experience of rice cultivation), as well as areas far from this region. In the border area, farmers had opportunities to import suitable rice varieties as well as to adopt rice-farming techniques from Gambia. Thus, the TE level of farmers living in a village with easier access to Gambia (near a trading centre or national road) tended to be higher. Groundnut and pearl millet had high TEs with a peak at 0.9 (Fig. 1) underlining the long experience of the farmers growing these crops. Likewise, the very high TE of maize was the result of a well-established farming system and a strong incentive to recover the high costs of the necessary fertilisers.

TEs found in previous studies in West African countries were 0.35–0.90 for rice farming and 0.45–0.87 for other crops (Table 4). These are relatively lower than our results. Sherlund *et al.* (2002) showed that including natural environmental factors such as soil, topography, pests, weeds, and weather conditions lead to higher TE levels compared to no inclusion of these factors. This means that if environmental factors are controlled or identical among farmers, TE will be higher. Hence, the environmental conditions in our study area may have been comparable amongst farmers and therefore may not have (negatively) influenced TE levels.

4.3 Determinants of TEs

Weeding time was a significant negative factor affecting the TE of lowland rice, groundnut, and pearl millet (Table 3). In the study area, weeding is carried out by both inter-row weeding using an animal drawn hoe (a "houe sine" or "houe occidentale"; Starkey, 1989) using a donkey, cow, or horse, and within-row manual weeding using a hand hoe. This weeding method was almost the same among farmers. A previous study in Gambia demonstrated that the manual within-row weeding had little effect on final crop yield compared to mechanical inter-row weeding only (Remington & Posner, 2000). In our sample, 56–81 % of weeding hours were manual weeding (data not shown). Therefore, a more selective weeding approach with a focus on mechanical inter-row weeding will decrease overall weeding time and increase TE levels.

The amount of nitrogen fertiliser applied in groundnut and pearl millet cultivation was a positive determinant factor of TE; however, it was not a significant factor for upland and lowland rice (Table 3). The significant and higher (compared to pearl millet) effect of nitrogen for groundnut is different from our expectation based

on the fact that groundnut root nodules provide nitrogen to the soil. If soil fertility is sufficiently high, the effect of applied nitrogen on TE will be none or small. Groundnut has been cultivated in Senegal without applying the necessary amount of nitrogen since the 1980s (Freud *et al.*, 1997); the amount supplied in the study area is equivalent to only one-sixteenth of the recommended amount (Ajeigbe *et al.*, 2014) and fields have been intensively cultivated without adequate fallowing, so the soils used for groundnut are deficient in nitrogen. Senegalese farmers may have overestimated the contribution of root nodules to the nitrogen supply in soil. Our results for pearl millet also show that inefficient pearl millet farmers need to increase the amount of nitrogen application in order to raise their TE. Senegalese farmers can obtain fertiliser through in-kind loan or subsidy program but the obtainable amount is limited in general. Thus, to increase the amount of nitrogen application, one solution is to make more use of animal manure because most farmers do not manage this resource properly.

The amount of nitrogen applied was not a significant factor for upland and lowland rice production. Water availability is a principal factor affecting the fertiliser effect on the yield. As upland rice easily suffers from drought and lowland rice is cultivated under more favourable water and fertility conditions, additional fertiliser application had little effect on increasing TE.

The seeding rate had a negative effect on the TE of lowland rice production; i.e. farmers need to decrease the seeding rate to increase TE. Surveyed farmers tend to sow more seeds than is efficient to avoid hazards such as bird attacks, competition with weeds, and losses from inappropriate management practices but the additional amount of the sown seeds did not contribute to increase the yield effectively. If there is no constraint in expanding inputs, the recommended seeding rate will produce a maximum yield, ceteris paribus. In case that, however, farmers' resource is restricted, it is not always appropriate to aim at the recommendation level. A feasible solution for inefficient farmers is to aim at the seeding level of efficient farmers who are under similar situation (i.e. production resource endowment).The seeding rate of pearl millet also had a negative effect on TE. However, the seeding situation of pearl millet is different from that of lowland rice. The average seeding rate of pearl millet is at the upper limit of the recommendation range, 3.5–5.0 kg ha^{-1} (Havard, 1986). Our result shows that the seeding rate of pearl millet, even in the range, can be reduced without decreasing the yield.

Table 4: *Overview of crop technical efficiency studies in some West African countries.*

Authors	Area	Crops	Estimated TE
Abdulai & Huffman (1998)	Ghana	Rice	0.72 (SFA)
Abdulai & Huffman (2000)	Ghana	Rice	0.73 (SFA)
Anang *et al.* (2016)	Ghana	Rice	0.61–0.63 (SFA)
Diagne *et al.* (2013)	Senegal	Rice	0.55–0.60 (SFA)
Okoruwa *et al.* (2006)	Nigeria	Rice	0.76–0.81 (SFA)
Seck (2016)	Senegal	Rice	0.27 (CRS), 0.32 (VRS)
Sherlund *et al.* (2002)	Côte d'Ivoire	Rice	0.56 (VRS), 0.35 (SFA) [†]
Sherlund *et al.* (2002)	Côte d'Ivoire	Rice	0.90 (VRS), 0.76 (SFA) [‡]
Abdulai *et al.* (2013)	Ghana	Maize	0.74 (SFA)
Aye & Mungatana (2010)	Nigeria	Maize	0.72 (CRS), 0.78 (VRS), 0.79 (SFA)
Aye & Mungatana (2013)	Nigeria	Maize	0.80 (CRS), 0.86 (VRS), 0.87 (SFA)
Binam *et al.* (2004)	Cameroon	Maize	0.75 (SFA)
Binam *et al.* (2004)	Cameroon	Groundnut	0.71 (SFA)
Kane *et al.* (2012)	Cameroon	Groundnut & Maize	0.44 (CRS), 0.67 (VRS)
Thiam & Bravo-Ureta (2003)	Senegal	Groundnut	0.70 (SFA)
This study	Senegal	Rice	0.76–0.88 (CRS)
		Maize	0.94 (CRS)
		Groundnut	0.89 (CRS)
		Pearl millet	0.90 (CRS)

Note: CRS: Data Envelop Analysis was conducted with Constant Return to Scale assumption, VRS: Data Envelopment Analysis was conducted with Variable Return to Scale assumption, SFA: Stochastic Frontier analysis was conducted.
[†]: Environmental factors were excluded in the TE measurement variables. [‡]: Environmental factors were included in the TE measurement variables.

Cultivated area was a negative factor for TE only for lowland rice. Land development for lowland rice production tends to occur first in the most favourable locations and then spreads to less favourable sites, which are located at the boundary between lowland and upland and therefore are at risk of soil degradation (e.g. soil erosion). As the proportion of less favourable land being cultivated increases, the area of cultivated land will have a negative effect on TE. This relationship between land area and TE was reported in previous studies also (Okoye *et al.*, 2009; Aye & Mungatana, 2010; Kane *et al.*, 2012). These authors focused on small-scale farmers (0.61–1.20 ha) using traditional farming practices (manual labour and crude implements) and they explained the negative relationship in terms of labour shortages (Kane *et al.*, 2012) or timing of input application (Aye & Mungatana, 2010). On the other hand, a positive relationship was found by Ogundele & Okuruwa (2006) in places where larger-scale farming (2.59–6.52 ha) was dominant. The technological difference between these small and larger farms typically appeared to be the degree of mechanisation. Mechanical equipment functioned more efficiently as the size of contiguous farmland increased.

A delay in sowing time is a significant negative factor for TE in upland rice, lowland rice, groundnut, and maize. Pearl millet is the exception, possibly because it is less sensitive to drought than the other crops. As the rainy season in the study area is very short (four months), drought-sensitive crops may be exposed to water shortages and drought-related damage when sowing is delayed. Therefore, a delay in sowing negatively affects the TE of crops that have low drought resistance.

Participation in a farmers' association positively affected the TE of lowland rice production especially, as reported also in earlier studies (Audibert, 1997; Kane *et al.*, 2012; Seck, 2016). This positive association might be the result of farmers sharing their experiences and exchanging ideas on cultivation techniques. The farming technique for lowland rice, especially for water management, is relatively new and difficult for farmers, which perhaps explains why the positive coefficient of participation was only significant for lowland rice in this study.

For upland rice and lowland rice, TE was positively related to the variable of years of cultivation experience as reported also by Seck (2016). To enhance the TE levels, therefore, upland and lowland rice farmers need to compensate for their short cultivation experi-

ence. Participating in a training program can offset the deficiencies in farming experience and knowledge.

4.4 Production potential and concluding remarks

The inefficiency rates of crop production $(1 - \text{TE})$ were 24, 12, 11, 6, and 10 % in upland rice, lowland rice, groundnut, maize, and pearl millet, respectively. In case that the current efficiency levels are base setting and 100 % efficiency level is a target, or potential setting, the potential yields of the five crops will increase at 0.84, 1.70, 0.82, 1.06, and 0.66 t ha^{-1}, respectively. These yield levels can be achieved by optimising the existing farming practices. The fact that TE distribution and its influencing factors are different among crops, could be very useful for preparing an effective program of agricultural extension for the farmers in the study area. Although upland rice has the highest improvement potential, an expansion of upland rice may not be feasible for Senegalese farmers owing to its vulnerability to droughts. Therefore, a focus should be put on lowland rice, groundnut, and pearl millet.

It should be noticed, moreover, that even if the TE levels can be increased, there will still be a yield gap if compared to actual yield levels of some West African countries (Binam *et al.*, 2004; Aye & Mungatana, 2013; Anang *et al.*, 2016). Thus, in order to enhance the production levels, additional crop improvement strategies will be necessary. Amelioration of farmers' accessibility to improved agricultural technologies (e.g. hybrid seeds, chemical fertiliser, irrigation infrastructures, or agricultural mechanisation) should be the preferred approach.

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