

Self-sufficiency policy and irrigated rice productivity in the Senegal River Valley

Mandiaye Diagne · Matty Demont ·
Papa Abdoulaye Seck · Adama Diaw

Received: 30 October 2011 / Accepted: 27 November 2012 / Published online: 21 December 2012
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Abstract Senegal's high dependence on rice imports exposes the country to international market shocks with concomitant serious risks for food security. Since 2011 and triggered by high international prices, several initiatives to upgrade the rice value chain have emerged in the private sector. However, the major constraint private investors are currently facing is the insufficient supply of Senegal River Valley (SRV) paddy rice, implying that investment in productivity is becoming vital for the continuation of their operations, which are currently running below their optimum. The Senegalese government is investing heavily in the national rice sector, with the ambitious objective of achieving self-sufficiency in the year 2015. However, the program focuses primarily on extension of the area grown rather than increased productivity. We provide econometric support for policy making by assessing the determinants of productivity and technical efficiency in irrigated rice production systems through a five-year panel dataset of small-scale irrigated rice farms in the SRV. We found that due to the exacerbation of biological and institutional constraints in the SRV, rice growers had difficulties in maintaining productivity of their land. These constraints prevented them from further intensification, jeopardizing the national objective of self-sufficiency. Farmers exhibited modest technical efficiency levels, suggesting that, in addition to the proposed intensification strategies, substantial efforts in extension services will be required in order to achieve the goal of self-sufficiency. Improved weed and bird control as well as technological, organizational and institutional improvements were

identified as key factors for boosting productivity and technical efficiency and, hence, these are target areas needing attention by Senegalese farmers and policy makers in their quest for increased food security.

Keywords Irrigated rice · Food self-sufficiency program · Farm management fixed-effects · Technical efficiency

Introduction

Rice production in Sub Saharan Africa (SSA) grew at 3.23 % per annum between 1961 and 2006 while the yearly population growth rate was 2.90 % during the same period. However, the annual increase in rice consumption of 4.52 % during this time explains the widening gap between supply and demand. This has been covered by increasing reliance on imports (Africa Rice Center (WARDA) 2007). Larson et al. (2010) showed that the share of rice calories in the African diet increased from 5 % in 1965 to 8 % in 2005, while the share of maize and tubers has been relatively constant. Thus, the ratio of production over consumption in SSA, measured by the self-sufficiency ratio, declined steadily from 112 % in 1961 to 61 % in 2006. The increase in rice consumption can be largely attributed to strong demand in Southern and West Africa with, respectively, average annual consumption growths of 11.58 % and 6.55 % during the period 2001–2005 (Africa Rice Center (WARDA) 2007).

Earlier, Randolph (1997) had shown that in the Sahel region, the share of rice in total consumption had grown from 10 % to 15 % during the period 1961–1992. The share of other coarse grains such as wheat and maize had increased, respectively, from 2 % to 6 % and from 6 % to 7 % in the same period, while the combined shares of the traditional grains, millet and sorghum, had fallen from 81 % to 70 %. The two main factors that contributed to the growth in rice demand were the increases in both population and the

M. Diagne (✉) · M. Demont
Africa Rice Center (AfricaRice), BP 96, Saint Louis, Senegal
e-mail: m.diagne@cgiar.org

P. A. Seck
Africa Rice Center (AfricaRice), BP 2031, Cotonou, Benin

A. Diaw
University of Gaston Berger, BP 234, Saint Louis, Senegal

importance of rice in Sahelian diets owing to rapid urbanization (Randolph 1997; Reardon et al. 1997).

Now the major increases in rice demand are in West Asia, South America and SSA due to migration of rural people to the towns and cities, leading to changes in diets based on other cereals or root crops to rice (Hossain 2007). West-African consumers have been gradually shifting their consumption patterns from traditional coarse grains (maize, millet and sorghum) to non-traditional grains (wheat and rice) owing to their increased time spent working away from home. Urban working women have less time for food preparation and have a tendency towards “convenience” sources of calories (Reardon 1993). Urban-biased policies have further contributed to this trend by encouraging food imports, their focus on rice being primarily driven by a desire to satisfy the demands of growing urban populations for affordable food rather than as a goal to improve the livelihoods of rural producers (Demont et al. 2013a; Moseley et al. 2010). In Senegal, for example, during the colonial period under the French administration, cheap broken rice from Asia was imported in large quantities in order to keep food prices under control and, at the same time, groundnut production was promoted as an important cash crop (Brüntrup et al. 2006; Demont et al. 2013a; b).

Senegal is the third-largest rice importer in Africa, after Nigeria and Côte d'Ivoire (USDA 2011a; USDA 2012). Senegalese rice consumption exceeds by far domestic production which meets only about 28 % of the country's requirements and of this domestic production 27 % is used for subsistence (Gergely and Baris 2009). The remaining 73 % is mostly sold to the nearest domestic urban markets in the North of Senegal (Saint Louis and Louga) and, more recently, to the capital city, Dakar (Demont and Rizzotto 2012). Rice is currently the main staple food in Senegal, the annual per capita consumption having risen sharply since independence from 50 kg in the 1960s to 60 kg in the 1990s (Tardif-Douglin and Diouf 1998) and to 92 kg in 2011 (USDA 2011b).

About 72 % of the rice consumed in Senegal is imported (Gergely and Baris 2009). With such high dependence on imports, Senegal is exposed to international market shocks, sometimes with grave consequences for its food security and political stability, as attested by the violent riots during the 2008 food crisis (Moseley et al. 2010; Seck et al. 2010). Demont and Rizzotto (2012) argued that if Senegal wishes to reduce import dependency, policy-makers and stakeholders will need to gradually upgrade Senegal River Valley (SRV) rice value chains according to the following three-stage policy sequence: (i) investment in post-harvest product-quality infrastructure, (ii) scaling-up of quality produce by investment in productivity, aggregation and storage infrastructure, and (iii) adoption of sector-wide marketing strategies that enhance the chain competitiveness of domestic relative to imported rice.

Since 2011 and triggered by high international prices, several initiatives to upgrade the rice value chain have emerged in the private sector. First, Senegalese rice importers officially launched a joint venture with producers and processors under the name SPCRS (*Société de Promotion et de Commercialisation du Riz Sénégalais*). The company purchases local paddy rice in the SRV through contracts with milling factories and farmers and markets milled rice to urban Senegalese consumers while governing quality along the chain (Mohapatra 2011). Secondly, the Belgian impact investor, Durabilis, started contracting with SRV farmers and millers to market quality SRV rice in Dakar. Thirdly, the private company Vital has made massive investments in high-quality milling infrastructure in order to supply quality SRV rice to urban markets in Senegal. These recent developments suggest that the first stage of Demont and Rizzotto's (2012) policy sequencing framework has been well initiated. However, the major constraint private investors are currently facing is the insufficient supply of SRV paddy rice, implying that investment in productivity is becoming vital for the continuation of their operations, which are currently running below their optimal scale (AfricaRice 2012).

The improvement of agricultural productivity is still of high importance in developing countries where agriculture is the main source of income (Fulginiti and Perrin 1998) and where increasing agricultural productivity has the potential to substantially contribute to poverty reduction (Jayne et al. 2003). In Senegal, 60–70 % of the population live in rural areas and, according to a World Bank (2006) survey, 57.5 % of rural households were classified as “poor” in 2001–2002. Due to the high rice imports, Senegal was hit very hard by the recent increase in food prices. In 2008, the world price of Thai 25, the rice type most imported by Senegal, almost tripled in half a year (FAO 2009). In April 2008 in the wake of the crisis, the Senegalese government launched the GOANA program (*Grande Offensive Agricole pour la Nourriture et l'Abondance*). In this programme massive investments in the national rice sector are being carried out with the ambitious objective of achieving self-sufficiency in the year 2015. In order to achieve this goal, the programme has to raise paddy rice production from 200,000 t to at least 1,500,000 t (MAE 2008).

In SSA, many large scale irrigation programs have failed in the past, but since the 1980s rates of return for irrigation projects have dramatically increased thanks to improvements in institutions, technologies and market opportunities. Small-scale irrigation projects have been especially successful (World Bank 2008). As the main objective of the GOANA program is based on production growth through spatial and temporal extension, it largely ignores other sources of productivity growth, i.e. through technical and organizational improvement. Spatial extension involves bringing back neglected irrigated rice schemes into production and

development of new ones. Temporal extension consists of improving conditions that favour double cropping, i.e. cropping during both the wet and dry seasons. This is particularly important for small-scale and resource-poor rice farmers in the SRV, where there is still considerable scope for either boosting productivity levels through technological innovation (Demont et al. 2009; Fall 2005; Fisher et al. 2001; Kebbeh and Miézan 2003) or raising technical efficiency (TE) levels through organizational innovation (Le Gal and Papy 1998; Poussin et al. 2006).

Moreover, in addition to biological constraints such as bird damage and competition from weeds (de Mey et al. 2012), SRV rice farmers frequently face institutional constraints due to market imperfections such as breakdown of fertilizer supply and weakness of the credit system. As a consequence, conventional inputs are often not applied on the recommended dates and at the recommended rates. The Rice Integrated Crop Management (RICM) options¹ in the SRV along with the use of improved varieties, contributed to increasing average yield from 3.8 tha^{-1} to 5.5 tha^{-1} (Defoer et al. 2004). Rice growth models predict a yield potential of irrigated rice in the Sahel of 9–12 tha^{-1} (Dingkuhn and Sow 1997). The latter was confirmed at farm level in the SRV, where yields of 12 tha^{-1} have been reported in the hot dry season (Wopereis et al. 1999) and even during the wet season by some of the farmers that were surveyed for this study (Table 1). Despite this performance, the gap between on-farm and potential yields is still substantial.

While some basic information is available on the potential impact of innovation in the irrigated rice sector in the SRV (Demont et al. 2009; Fall 2005; Fisher et al. 2001; Kebbeh and Miézan 2003), so far no econometric estimates are available on actual productivity and TE levels of irrigated rice. In order to make informed decisions about increasing productivity, Senegalese policy makers need to be informed about the characteristics and potential of the current state-of-the-art production system in the irrigated rice sector. More specifically, they need to know which factors contribute to productivity, which contribute to technical efficiency (TE) and which contribute to both, so that they can target policy interventions more precisely towards priority areas in the struggle towards achieving increased food security in Senegal. Therefore, in this paper we assess the determinants of productivity and TE of small-scale irrigated rice farms in the SRV.

The article is organized as follows. After this introduction, we present our theoretical framework in the next section. Section 3 describes the data. In Section 4, the results

are presented. Finally, the results are discussed and conclusions drawn in Section 5.

Analytical framework

In the empirical literature on productivity analysis of firms, non-parametric and parametric frontier approaches are commonly used. The major limitation of non-parametric approaches, particularly those based on data envelopment analysis, is the fact that they assume no sampling error and attribute all derivation from the production frontier to inefficiency. As many factors affect rice production in the SRV, of which some are beyond the control of farmers (e.g. weather, institutional constraints such as delayed provision of state-controlled credit, lack of machinery and organizational constraints), this assumption may not be valid for our case study. Parametric approaches, instead, account for those factors and enable isolation of the determinants of productivity and efficiency from uncontrolled factors. Therefore, to inform policy decision-making on increasing rice production in the SRV with the aim of achieving the national goal of self-sufficiency, we tested several alternative parametric models in order to specify the underlying production system of irrigated rice.

Parametric models

Several parametric approaches are used in the productivity literature, including (i) stochastic frontier models (Ahmad and Bravo-Ureta 1996; Bravo-Ureta and Pinheiro 1993); (ii) production function specifications based on fixed effects, and (iii) deterministic frontier models. The common weaknesses of these approaches are the structural restrictions imposed by the functional form. The stochastic parametric frontier model allows the effect of unknown random variables to be separated from the effects of inefficiency and assumes that the inefficiency variables are uncorrelated with other variables included in the model. The fixed-effects model, in contrast, allows for correlation between TE and the other explanatory variables, and takes into account some potentially omitted variables (Ahmad and Bravo-Ureta 1995; Alvarez and Arias 2004; Murillo-Zamorano 2004).² The deterministic parametric frontier model, on the other hand, is criticized for its sensitivity to outliers.

Given our aim of guiding policy makers on productivity and TE of SRV rice growing and the availability of a 5-year panel database of rice growers' practices (see Data section),

¹ The improved technologies developed in the 1990s in the SRV were assembled to make up the RICM recommendations in the early 2000s, giving farmers the choice of using one or a subset of components depending on their resource endowments and technical and socioeconomic constraints (Kebbeh and Miézan 2003).

² In econometrics, endogeneity bias arises when important regressors are omitted, or in the presence of measurement error or simultaneous occurrence of at least one regressor and the dependent variable, and consequently the parameters of interest are not consistently estimated (Wooldridge 2001).

we have opted for a parametric approach based on the fixed-effects production model as the stochastic frontier model was shown to be inappropriate in our case.³ To take into account management effects on the productivity of production factors, a farm dummy variable is introduced in the production function as a proxy for farmer management or individual farmer effects (Schmidt and Sickles 1984), which is then used as a measure of TE (Hoch 1976). Following Ahmad and Bravo-Ureta (1995, 1996), we use fixed-effects Cobb-Douglas (CD) (McDonald and Moffitt 1980) and simplified translog production functions. The simplified translog production function is preferred to the standard translog because of possible multicollinearity problems in the latter (Fan 1991). We introduce technical change into the CD function through two alternative specifications. Our first specification includes a time variable, T , to capture technical progress within the period and assumes invariant TE:

$$\ln Y_{it} = \alpha_0 + \sum_i \alpha_i D_i + \sum_k \beta_k \ln X_{kit} + \delta T + v_{it}, \quad (1)$$

where the subscripts i , t and k represent respectively farms, year or time and inputs, Y_{it} is output (rice production), α_i , β_k and δ are parameters to be estimated, D_i is a farm dummy variable having a value of one for the i th farm and zero otherwise, X_{kit} represents production factors (land, labour, seed, fertilizers, herbicides and services), T is time, and v_{it} is the usual error term. Technical change is captured through the expression δT . The second CD function is specified through a set of time dummies $\sum_t \delta_t DT_t$, where DT_t is a dummy variable having a value of one for the t th time period and zero otherwise, and δ_t are parameters to be estimated.

³ The stochastic frontier specification has the property of embodying a deterministic frontier function and two random error components. The deterministic function represents the potential frontier production or the farm's best practice technique. The first error component, denoted by v , represents the statistical error or other random factors such as weather that are beyond the farm's control. v is positive, negative or zero. In the presence of these errors, the production frontier may vary across farms and over time for the same farm. The second error component, denoted by u , represents the technical inefficiency of the farm. u is either zero or negative. Then, if there are no errors v , the farm would realize the maximum attainable production, depending on whether it uses the best practices ($u=0$) or not ($u<0$) (Kalirajan and Shand 1999). The appropriateness of the stochastic frontier model specification can be tested to check if the incorporation of the random error component representing technical inefficiency is justified. Otherwise the stochastic frontier model is not justified and leaves a specification that can be consistently estimated by ordinary least squares (Coelli 1996). In our study, we preliminarily estimated the translog and Cobb Douglas stochastic frontier functions and the results have shown that the stochastic frontier specification is not appropriate in our case, hence our choice of the fixed-effects model.

Our simplified translog production function explicitly allows for interaction between inputs and time:

$$\ln Y_{it} = \alpha_0 + \sum_i \alpha_i D_i + \sum_k \beta_k \ln X_{kit} + \sum_k \phi_k \ln X_{kit} T + \delta T + \lambda T^2 + v_{it} \quad (2)$$

where α_0 , α_i , β_k , ϕ_k , δ and λ are parameters to be estimated. As in Fan (1991), the parameters β_k and ϕ_k are used to calculate the production elasticity for each input. The latter is obtained by the logarithmic derivative of the production function in Eqs. (1) and (2), i.e. $\partial \ln Y / \partial \ln X_{kit} = \beta_k$ from Eq. (1) and $\partial \ln Y / \partial \ln X_{kit} = \beta_k + \phi_k T$ from Eq. (2). The elasticity is the responsiveness of production (in per cent) for a one per cent increase in respective inputs.

From these equations, the farm-specific measures of invariant TE can be derived as $TE_i = \exp(\alpha_i) / \max[\exp(\alpha_i)]$, where the denominator represents the highest predicted value for the i th farm. To allow for varying TE and assuming that farm-specific effects vary over time, as suggested by Mundlak (1978), the parameter α_i in Eqs. (1) and (2) is replaced by the expression $\alpha_i + \rho_i T$, where ρ_i is a farm-specific slope parameter with respect to time. Varying TE is estimated in two steps (Cornwell et al. 1990; Kumbhakar et al. 1999). First, Eqs. (1) and (2) are estimated to obtain consistent estimates of α_0 , β_k , ϕ_k , δ and λ . Next, the residuals from the first step, $\hat{\varepsilon}_{it} = \mu_{it} + v_{it}$, which include farm-specific effects ($\mu_{it} = \alpha_i + \rho_i T$) as well as the usual error term (v_{it}), are regressed through ordinary least squares, i.e.

$$\hat{\varepsilon}_{it} = \sum_i \alpha_i D_i + \sum_i \rho_i D_i T + v_{it}, \quad (3)$$

where v_{it} is independent and identically distributed $N(0, \sigma^2_v)$. The efficiency indicator is finally calculated as $\hat{\mu}_{it} = \hat{\alpha}_i + \hat{\rho}_i T$ and TE at each data point is then obtained as

$$TE_{it} = \exp(\hat{\mu}_{it}) / \max[\exp(\hat{\mu}_{it})], \quad (4)$$

where the denominator represents the highest predicted value in the t th period.

The estimation approach proposed above is called the "least squares dummy variables" (LSDV) approach, as we are using dummy variables to estimate the fixed or farm-individual effects with the least squares estimation techniques (Greene 2002). The hypothesis test and model selection are based on Likelihood Ratio test techniques to verify whether a restricted or simpler model (Cobb Douglas model) can be preferred or not to an unrestricted or more general model (Translog model) (Baltagi 2005; Greene 2002).

Determinants of technical efficiency

For policy purposes, it is useful to identify the sources of technical inefficiency, which can be done through a second

estimation step in which the relationship between farm characteristics and the computed TE scores from the first estimation step is estimated (Bravo-Ureta and Pinheiro 1997; Coelli et al. 2005). Therefore, in our empirical analysis in the remainder of the article, we (i) select the model that best represents the production system of irrigated rice farming in the SRV, (ii) derive the TE scores, (iii) transform the efficiency score, which falls between zero and one, through a logistic function to avoid the problem of obtaining estimated values outside the [0–1] interval (Amara et al. 1999; Romain and Lambert 1995; Tauer 1993), i.e. $Effic_{it} = \ln(TE/(1 - TE))$, and (iv) analyze the determinants of the transformed efficiency scores through the following model:

$$Effic_{it} = b_0 + \beta'Z_{it} + \sigma_{it}, \quad (5)$$

where Z_{it} is a vector of variables (inputs, farm and socioeconomic characteristics) related to technical inefficiency, β a vector of parameters to be estimated, and σ_{it} the error term.

Data

The Senegal River basin, located in West Africa, covers 1.6 % of the continent and spreads over four countries (Guinea, Mali, Mauritania and Senegal) with a 1,790 km long river (FAO 1997). On the Senegalese side, the SRV has an irrigation potential of 240,000 ha. The SRV is subdivided into three zones: the Delta, the Middle Valley and the Upper Valley. In 2008, the entire irrigation scheme covered 95,030 ha, 54 % of which were suitable for rice (SAED 2008), characterized by medium and large irrigation schemes in the Delta, and small to medium schemes in the Middle Valley. Rice is predominantly direct-seeded (wet broadcast) in large schemes in the Delta and Middle Valley, and transplanted in smaller, village-based schemes in the Upper Valley (Dingkuhn 1997). During the period 2002–2006, we surveyed a sample of farmers randomly selected from a list of irrigated rice farms provided by the national extension agency SAED (*Société Nationale d'Aménagement et d'Exploitation des terres du Delta du fleuve Sénégal et des vallées du fleuve Sénégal et de la Falémé*). The farmers included in the survey were drawn from the population of rice farmers who were aware of RICM or adopted at least one of its components, depending on their ability, socio-economic production environment and resource endowments. Farmers who stopped growing rice were replaced by farmers randomly drawn from the list.

The sample was stratified between the first two main production zones (Delta Valley and Middle Valley), which

represent 89 % of paddy rice production in the SRV (SAED 2007). The result is an unbalanced panel⁴ dataset of irrigated rice farmers' agricultural practices with sample sizes of 71, 106, 105, 105 and 98 farmers, corresponding to the years 2002, 2003, 2004, 2005 and 2006, respectively, and totalling 485 farmer $\times$ season observations. The data were collected during the wet seasons which represent, on average and in area terms, 83 % of rice cropping in the SRV during 1991–2007 (SAED 2007).

The output of rice is the total production of paddy rice measured in tons. The production factors were aggregated into six categories, i.e. land, labour, seed, fertilizers, herbicides and services. The first five factors were expressed in quantitative terms. The category “services” was expressed in value terms and included the expenditures for quasi-fixed inputs such as land preparation, irrigation, harvest and post-harvest services mainly conducted by private contractors. Family and hired external labour were aggregated and assumed to be equally productive.

In Table 1, we report some descriptive statistics of the production factors and farm characteristics of our sample. Despite the constraints mentioned above, the average yield level during the surveyed period amounted to 5.32 t.ha⁻¹, which is well above the average of 3.62 t.ha⁻¹ in irrigated rice cultivation in sub-Saharan Africa (Rodenburg and Johnson 2009). However, with regard to the yield potential as mentioned above and within a context of availability of improved technologies, this performance could be considered as a technical regression. The highest average yield in our period of study was attained in 2004 and amounted to 5.88 t.ha⁻¹ and the lowest in 2006, i.e. 4.04 t.ha⁻¹. The year 2006 was particularly problematic because of the intensification of bird damage and disturbance of input supply (de Mey et al. 2012). Therefore, the maximum yields attained in this period varied from 9.01 to 12 t.ha⁻¹ in our sample showing that the theoretical yield mentioned above can be attained at farm level.

Farms are quite small in the Middle Valley, with an average farm size of only 0.59 ha and paddy rice production of 3.22 t per farm. Input use is larger in the Delta Valley due to larger farm sizes, averaging 2.43 ha and producing 11.59 t of paddy rice per farm. Heterogeneity of farm size is, however, somewhat more pronounced in the Delta Valley than in the Middle Valley. Farm characteristics also differ between the two zones, e.g. the average age of the farm head is 44 years in the Middle Valley and 51 years in the Delta Valley and the average experience in rice growing is 18 years in the Middle Valley and

⁴ The panel dataset is unbalanced which means that over the subsequent survey years, some farmers stopped producing or left the database and new farmers have been added. The total number of unique farmers was 132, hence the total number of farm dummies was 132 – 1 = 131, i.e. one farmer was set as the reference.

Table 1 Descriptive statistics of the variables in the panel dataset of irrigated rice farms in the Senegal River Valley (2002–2006)

Variable	Description	Mean	St. Dev.	Min	Max
Production	Harvested quantity of paddy rice (tons)	7.34	9.03	0	73.25
Land	Area sown with rice (ha)	1.50	1.90	0.10	12.50
Yield	Yield (tons per ha)	5.32	1.84	0	12
Labor	Family and external labor (man $\times$ days)	203	586	11	7463
Seed	Seed use (kg)	195	259	10	1,750
Fertilizer	Fertilizer use: Urea and DAP (kg)	504	666	30	4,500
Herbicides	Herbicide use: Propanil and Weedone (litres)	10.10	12.29	0	75
Services	Land preparation, irrigation, harvest and post-harvest costs (10^6 FCFA ^a)	0.21	0.23	0.01	1.91
Age	Age of farm head	47.65	12.29	23	83
Experience	Number of years of experience in rice cultivation	23.37	13.55	0	54
UseASI	Use of ASI thresher (1=yes; 0=no)	0.46	0.50	0	1
Credit	Use of formal credit (1=yes; 0=no)	0.88	0.32	0	1
Sahel	Use of Sahel varieties (1=yes; 0=no)	0.80	0.40	0	1
CertSeed	Use of certified seeds (1=yes; 0=no)	0.79	0.41	0	1
ModeSeed	Sowing mode (1=direct seeding, 0=transplanting)	0.88	0.31	0	1
Leveling	Smooth manual levelling of plot (1=yes; 0=no)	0.60	0.50	0	3
GP	Type of area development (1 if GP ^b ; 0=otherwise)	0.76	0.42	0	1
Zone	Production zone (1=Delta; 0=Middle Valley)	0.49	0.50	0	1
DomAct	Dominant activity (1=farming; 0=off-farm)	0.49	0.50	0	1
DateSow	Date of sowing before August, 15 (1=yes; 0=no)	0.66	0.47	0	1
BirdChase	Bird chasing (1 if yes; 0=no)	0.68	0.47	0	1

Sample size $n=485$, except for the variable *Herbicides*, where $n=477$

^a €1=655.957 FCFA. FCFA stands for *Franc Communauté Financière d'Afrique* and is the common currency used in the Franc zone in Africa. The Franc zone is an economic, monetary and cultural area made up of France and 15 African states.

^b GP (*Grand Périmètre*) = Large irrigation schemes (or perimeters). In the SRV there are two dominant irrigation schemes: large irrigation schemes (*Grand Périmètres*—GP) and village level schemes (*Périmètres Irrigués Villageois*—PIV). The two types of schemes differ in size, plot size, soils and organization. The PIVs cover an area less than 50 ha and are cultivated by farmers from a single village while the GPs can stretch to more than 1,000 ha and are cultivated by farmers from different villages

29 years in the Delta Valley. The variances reported in Table 1 also suggest that experience is more heterogeneous than age.

Results

Estimation of the models

Based on our analytical framework, the following six models were estimated and compared: (i) CD fixed-effect with a variable time and time-unvarying TE (CDvu), (ii) CD fixed-effect with a dummy time variable and time-unvarying TE (CDdu), (iii) simplified Translog with a variable time and time-unvarying TE (TLvu), (iv) CD fixed-effect with a variable time and time-varying TE (CDvv), (v) CD fixed-effect with a dummy time and time-varying TE (CDdv), (vi) simplified Translog with a variable time and time-varying TE (TVvv). The results are reported in Table 2, but before discussing them, we also report the conduct of various tests of hypotheses about the parameters to determine the fixed-

effects model that best fits our panel dataset (Table 3). The hypothesis of no farm-specific effects is rejected in all models, suggesting that the production technology of rice farming in the SRV is not only characterized by productive inputs but also by farm-specific management practices. The appropriate functional form is the simplified translog as the null-hypothesis of no cross-term between time and inputs (ϕ_k), and no time-square parameter (λ) is strongly rejected. The tests on the non-existence of technical change and the time-unvarying TE are rejected as well, suggesting that TE of irrigated rice farmers in the SRV is not constant over time. Hence, these tests suggest that the production system of irrigated rice farming in the SRV is best represented by a fixed-effects simplified translog production function with time varying TE (TLvv).

We report estimated coefficients of the alternative production function specifications in Table 2. The panel dataset displays limited farm-specific effects; 10–35 % of the farm dummies were significant at the 5 % level. This can be explained by the fairly homogenous management practices

Table 2 Parameter estimates generated by alternative production function specifications for irrigated rice farming in the Senegal River Valley

Variable	CDvu	CDdu	TLvu	CDvv	CDdv	TLvv
Intercept	-6.96 (-6.17)***	-5.32 (-4.70)***	-0.95 (-0.41)	-8.31 (-8.83)***	-8.86 (-11.10)***	-4.56 (-2.45)**
LnLand	0.067 (0.46)	0.189 (1.31)	0.469 (1.69)***	-0.067 (-0.57)	-0.092 (-0.93)	0.39 (1.79)*
LnLabor	0.018 (0.42)	0.033 (0.72)	-0.208 (-2.18)**	0.063 (2.05)**	0.065 (2.54)**	-0.169 (-2.33)**
LnSeed	-0.250 (-2.32)*	-0.150 (1.40)	0.143 (0.69)	-0.031 (-0.34)	0.075 (0.98)	0.28 (1.70)*
LnFertilizer	0.181 (2.71)**	0.161 (2.49)**	0.355 (2.72)***	0.163 (2.81)***	0.123 (2.56)**	0.225 (2.22)**
LnHerbicides	0.070 (1.86)**	0.025 (0.64)	0.132 (1.36)	0.052 (1.44)	-0.0004 (-0.02)	-0.001 (-0.02)
LnServices	0.79 (9.30)***	0.613 (6.99)***	0.081 (0.45)	0.75 (10.52)***	0.771 (12.57)***	0.35 (2.42)**
T	-0.1315 (-9.74)***		-1.49 (-1.96)**	-0.10 (-8.12)***		-1.36 (-2.34)**
T ²			-0.050 (-4.70)***		-0.0005 (-0.01)	-0.054 (-6.30)***
T_2003		-0.070 (-1.20)				
T_2004		-0.082 (-1.34)			0.008 (0.17)	
T_2005		-0.138 (-2.21)**			-0.063 (-1.31)	
T_2006		-0.557 (-9.30)***			-0.445 (-9.53)***	
T×LnLand			-0.108 (-1.21)			-0.167 (-2.42)**
T×LnLabor			0.087 (3.14)***			0.082 (3.59)***
T×LnSeed			-0.110 (-1.56)			-0.084 (-1.56)
T×LnFertilizer			-0.060 (-1.51)			-0.020 (-0.66)
T×LnHerbicides			-0.021 (-0.87)			0.003 (0.17)
T×LnServices			0.185 (3.23)***			0.145 (3.28)***
Adjusted R ²	0.85	0.86	0.87	0.83	0.89	0.89

The dependent variable is rice production measured in tons. The t-ratios are shown between brackets. Asterisk (*), double asterisk (**) and triple asterisk (***) denote variables significant at 10 %, 5 % and 1 % respectively

CDvu=CD fixed-effect with a variable time and time-unvarying TE

CDdu=CD fixed-effect with a dummy time and time-unvarying TE

TLvu=simplified translog with a variable time and time-unvarying TE

CDvv=CD fixed-effect with a variable time and time-varying TE

CDdv=CD fixed-effect with a dummy time and time-varying TE

TLvv=simplified translog with a variable time and time-varying TE

Table 3 Hypothesis tests on the production technology in irrigated rice farming in the Senegal River Valley

Hypothesis	Null-hypothesis	F-value	Prob. > F	Decision
No farm-specific effects				
CDvu	$\alpha_i=0$	1.52	0.0014	rejected***
CDdu	$\alpha_i=0$	1.72	0.0001	rejected***
TLvu	$\alpha_i=0$	1.63	0.0002	rejected***
Functional form				
CDvu vs. TLvu	$\phi_k=\lambda=0$	11.48	0.0000	rejected***
No technical change				
CDvu	$\delta=0$	94.80	0.0000	rejected***
CDdu	$\delta_i=0$	36.41	0.0000	rejected***
TLvu	$\phi_k=\delta=\lambda=0$	24.41	0.0000	rejected***
Hicks-neutral technical change				
TLvu	$\phi_k=0$	8.81	0.0000	rejected***
Time unvarying technical efficiency				
CDvv	$\rho_i=0$	1.40	0.0136	rejected**
CDdv	$\rho_i=0$	1.72	0.0002	rejected***
TLvv	$\rho_i=0$	1.33	0.0311	rejected**

Asterisk (*), double asterisk (**) and triple asterisk (***) denote variables significant at 10 %, 5 % and 1 % respectively

in the SRV (de Mey et al. 2012). First, we observe that fertilizer use is a statistically significant production factor, a result which is robust among all specifications. Secondly, the variable “Services” is positive and significant in all but one of the specifications, suggesting that capital-intensive agricultural services are crucial production factors, particularly during land preparation and harvest/post-harvest operations.

In the TLvv model, with the exception of herbicide use, the production factors are all statistically significant at the 10 % level. Land, seed, fertilizer and services contribute positively to rice production. The insignificant coefficient for herbicide use in a standard CD or translog production function can be explained by the fact that weed control is not a productive input, but rather a damage abatement input which does not directly affect productivity, but indirectly through TE (Kuusmanen et al. 2006). This is confirmed in the second-stage analysis in the remainder of this article. The negative coefficient for labour may be explained by the extreme year 2006 in which farmers experienced dramatic bird damage (de Mey et al. 2012). If we capture the annual effects through year dummies (CDdu and CDdv), the coefficient becomes positive, but small. Nevertheless, the exacerbation of biological and institutional constraints in the SRV towards the end of the surveyed period 2002–2006 have caused a technical regression of irrigated rice farmers, reflected in the negative sign of the coefficient of the variable “time.” Farmers struggled to cope with adversity; the interaction terms between inputs and time suggest that they failed to maintain productivity levels of their land. At the

Table 4 Mean technical efficiency scores of irrigated rice farming in the Senegal River Valley according to alternative production function specifications

	CDvu	CDdu	TLvu	CDvv	CDdv	TLvv
2002	—	—	—	0.60	0.53	0.62
2003	—	—	—	0.55	0.65	0.60
2004	—	—	—	0.64	0.54	0.66
2005	—	—	—	0.55	0.62	0.57
2006	—	—	—	0.49	0.57	0.57
Mean	0.57	0.55	0.56	0.57	0.58	0.60
St. Dev.	0.14	0.13	0.13	0.11	0.11	0.10
Minimum	0.24	0.20	0.22	0.29	0.26	0.32

same time, they attempted to compensate the decline in land productivity through increased productivity levels of labour and services (measured through the production elasticities).⁵

Technical efficiency scores

The mean TE scores obtained through the fixed-effects models ranged from 55 % to 60 % with the highest scores obtained through the TLvv model (Table 4). Consistent with findings in the literature, we did not find any considerable differences in mean TE scores between the fixed-effects models, suggesting that TE is not conditional on the functional form (Ahmad and Bravo-Ureta 1996; Good et al. 1993; Maddala 2009). Table 4 illustrates the importance of uncontrolled factors. Almost all models reached their lowest TE levels in the extreme agricultural season 2006. The CDdv model is the only exception, which may be explained by the fact that the “bad year” effect is largely filtered out in the first stage through the year dummy T_{2006} , which features a highly significant coefficient. For the same reason, the “good year” 2004 is identified through the highest TE scores only by the CDvv and TLvv models as their production functions are based on a variable year rather than time dummies. In other words, if the seasonal effects are interpreted as exogenous productivity shocks and captured by dummies in the first stage, the TE scores reflect how farmers have coped despite uncontrolled factors. On the other hand, if seasonal effects are not captured, the TE scores reflect the impact of uncontrolled factors on TE.

We further observe that the TE scores feature the lowest variance in 2004. In Fig. 1 we depict the empirical frequency distributions of the TLvv model’s TE scores for the five agricultural seasons. First, the unimodal Gaussian shapes of the distributions indicate the existence of a small subset of technically efficient farmers. The graphs further visualize how

⁵ In the Translog specification as in equation (2) the production elasticity is $\partial \ln Y / \partial \ln X_{kit} = \beta_k + \phi_k T$. Thus if $\phi_k > 0$, production elasticity of input k is increasing and if $\phi_k < 0$, production elasticity of input k is decreasing (Fan 1991).

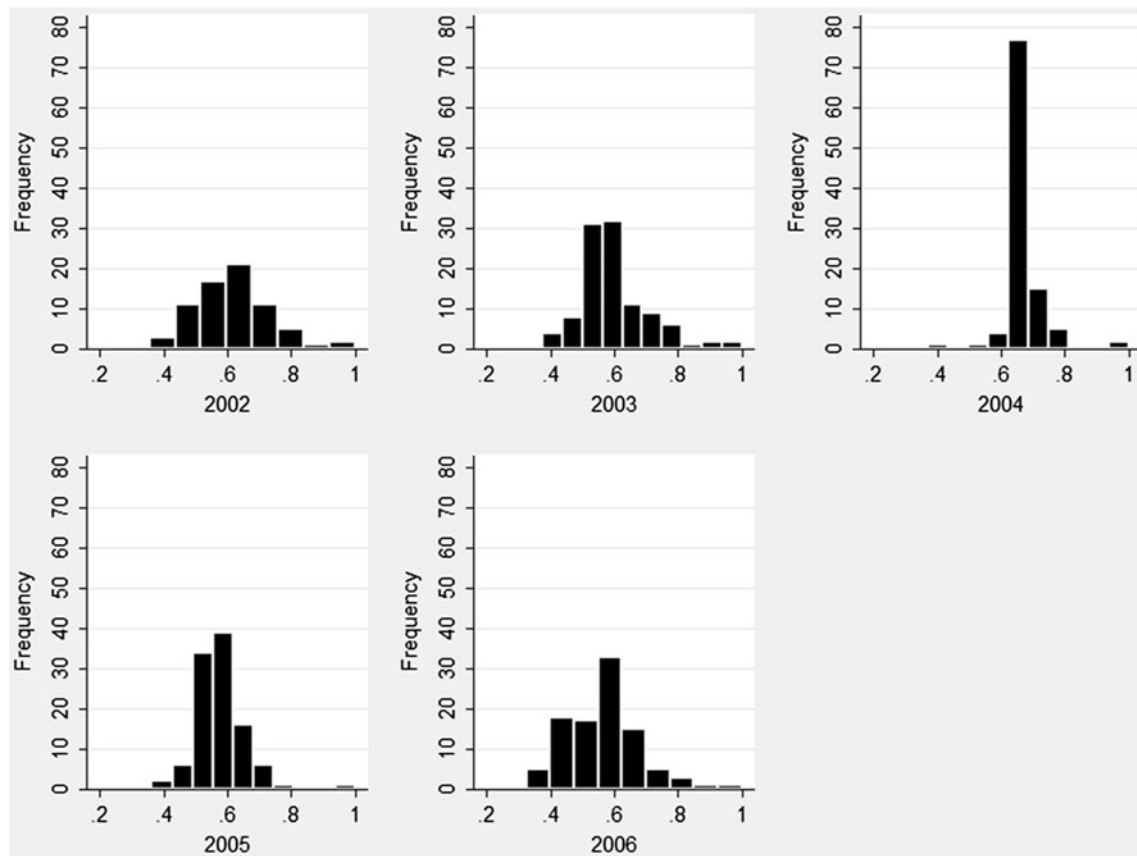


Fig. 1 Empirical frequency distributions of the technical efficiency scores obtained through the TLvv model on the panel dataset of irrigated rice farms in the Senegal River Valley during the period 2002–2006

a year without extreme disruptions enables farmers to achieve higher and more homogenous TE levels than a year with marked disruptions. In other words, if the institutional and biological constraints could be substantially relaxed, almost 80 % of the irrigated rice farms in the SRV could achieve 60–70 % of the highest recorded TE levels.

Determinants of technical efficiency

Wang and Schmidt (2002) argue that the two-stage model is subject to significant biases due to omitted variables in the first stage and to underdispersion of estimates of the inefficiency function in the second stage. However, their findings are based on a stochastic frontier specification rather than a fixed-effects model which allows for correlation between the standard factors in the production function and the TE variable. In our second-stage analysis, the logistic transformations of the TE scores obtained through the TLvv model are regressed on the production factors and a set of farm characteristics. As farm-specific and time effects are captured in the first stage, in the second stage the panel data are pooled. The results are reported in Table 5. The significant coefficient for fertilizer use suggests that fertilizers can play a double role in boosting productivity, i.e. directly as a productive input and

indirectly by raising TE levels. The negative and significant coefficient for the variable “services” is contradictory and indicates that external mechanized services affect irrigated rice farmers’ TE negatively. During our surveys, 23–50 % of farmers mentioned the poor quality of services and poor punctuality of service providers. Some farmers rely more on external services than others. Our econometric results suggests that, although services are a productive factor (significant coefficient in Table 2), increasing reliance on external services may come at the cost of increased exposure of the production system to inefficiency (Table 5).

The other production factors (land, labour, and seed) do not seem to significantly affect TE. The observed insignificant coefficient for herbicide use in our standard CD and translog production functions (Table 2) may confirm the role of weed control as a “damage abatement input” (Lichtenberg and Zilberman 1986) or “facilitating input” (Zhengfei et al. 2006) rather than a productive input. Alternatively, it could be interpreted as an input which does not directly affect productivity, but indirectly through TE (Kuosmanen et al. 2006). Indeed, in our second stage model we observe that both damage abatement inputs, i.e. herbicides and bird chasing efforts, significantly enhance TE. Chemical weed control is generally followed and completed by manual weeding which is one of the RICM

Table 5 Determinants of technical efficiency in irrigated rice farming in the Senegal River Valley

Variable	Coefficient	Standard error	t-value
Intercept	0.013	0.144	0.09
Land	−0.093	0.128	−0.72
Labour	−0.00008	0.00006	−1.24
Seed	0.00002	0.0008	0.03
Fertilizer	0.0005***	0.0002	3.50
Herbicides	0.010**	0.005	2.31
Services	−0.831***	0.268	−2.79
Age	0.0004	0.002	0.19
Experience	−0.0005	0.002	−0.23
UseASI	0.130***	0.049	2.63
Credit	−0.013	0.079	−0.16
DateSow	0.088*	0.053	1.65
Sahel	0.161***	0.057	2.80
CertSeed	−0.031	0.060	−0.51
BirdChas	0.217***	0.050	4.31
DomAct	−0.037	0.066	−0.56
Levelling	−0.035	0.051	−0.68
Zone	−0.086	0.081	−1.06
ModeSeed	0.057	0.076	0.74
GP ^a	0.049	0.063	0.77
Adjusted R ² =0.13			

The dependent variable is the transformed TE scores. Sample size $n=472$. Asterisk (*), double asterisk (**) and triple asterisk (***) denote variables significant at 10 %, 5 % and 1 % respectively

^a GP (*Grand Périmètre*) = Large irrigation schemes (or perimeters). In the SRV there are two dominant irrigation schemes: large irrigation schemes (*Grand Périmètres*—GP) and village level schemes (*Périmètres Irrigués Villageois*—PIV). The two types of schemes differ in size, plot size, soils and organization. The PIVs cover an area less than 50 ha and are cultivated by farmers from a single village while the GPs can stretch to more than 1,000 ha and are cultivated by farmers from different villages

recommendations. In irrigated rice production in the SRV, pre-emergence herbicide application substantially facilitates manual weeding labour by reducing initial weed infestation levels (Demont et al. 2009; Rodenburg and Johnson 2009).

Our model of TE determinants further indicates that timing of sowing is binding. Suboptimal timing of sowing mainly occurs due to institutional constraints such as delays in the access to formal credit and machinery. However, the variable “obtainment of formal credit” itself is not significant, perhaps because it does not distinguish between farmers who choose not to use available credit and farmers who did not have access to credit. A better measure would have been whether there is a source of credit available to the farmer, at a reasonable cost, both in terms of time and money (Doss 2006). Another cause of delays in rice planting, which can stretch over multiple seasons, is the irregular availability of machinery for soil preparation and post-harvest operations.

The use of post-harvest technologies such as the ASI thresher-cleaner further significantly raises TE levels. Besides saving labour, the ASI thresher-cleaner also better preserves the quality of paddy rice during the threshing operation. Improved varieties such as the Sahel varieties, developed through classical breeding by the Africa Rice Center (ex WARDA/ADRAO), also significantly boost TE levels. Further, parallel to the findings of Sherlund et al. (2002) on rice production in Côte d’Ivoire, we do not observe any statistically significant evidence for the effect of human capital, measured through age and experience. The insignificance of the use of certified seed on TE is consistent with farmers’ complaints about the low quality of certified seed in the SRV during recent years, i.e. they hardly experience any advantage in using certified seed. Finally, as shown in Table 5, TE does not seem to be significantly affected by the mode of seeding, manual levelling of the plot, the production zone (Middle Valley or Delta), off-farm activities and the type of the irrigation scheme (large irrigation schemes cultivated by many villages or village level schemes cultivated by only one village).

Discussion and conclusions

Senegal’s high dependence on rice imports exposes the country to international market shocks with concomitant risks for food security. If Senegal wants to reduce import dependency, policy-makers and stakeholders will need to gradually upgrade rice value chains in order to enhance the competitiveness of domestic relative to imported rice. Recent initiatives in upgrading the rice value chain have led to the constraint of insufficient supply of paddy rice in the SRV, implying that investment in local rice productivity—in order to scale up local production—is crucial at this stage of development.

The Senegalese GOANA program attempts to relax this constraint, but is widely considered as being ambitious and unattainable without significant additional investment (Demont and Rizzotto 2012). It will require a minimum of 130,720 ha to be planted with rice at the national level, including nearly 116,000 ha in the SRV, while development of the area and seed stock needed would take 2 years at a minimum (USDA 2008). In 2008/09 SRV rice production increased by 52 % but the increase was attributed to a 54 % area expansion while rice yields remained constant. The rate of achievement of the GOANA target was 67 % in 2008/09 and 41 % in 2010/11 (SAED 2008; SAED 2012). At these rates, it is unlikely that GOANA will reach its target in 2015.

The GOANA program focuses primarily on spatial and temporal extension of the rice irrigation scheme and largely ignores other sources of productivity growth. During our 5-year study period, we observed a technical regression of irrigated rice farmers. Due to the exacerbation of biological and institutional constraints in the SRV,

farmers had difficulties in maintaining productivity of their land. These constraints prevented them from further intensification and extensification, jeopardizing the national objectives of self-sufficiency (de Mey et al. 2012). Due to market imperfections such as breakdowns of fertilizer supply and weakness of the credit system, conventional inputs are often not applied on the recommended dates and at the recommended rates preventing irrigated rice farmers from benefiting from the full package of improved technologies that are available.

Our evidence shows that several sources of productivity growth, i.e. beyond spatial and temporal extension, are largely untapped. Raising TE levels through organizational innovation is one of them. When conditions are optimal, most of the rice growers achieve decent TE levels that are fairly homogeneous. However, under suboptimal conditions, TE levels are low and heterogeneous, implying that some farmers are able to cope with adversity while others are not. Coping with adversity is difficult in the SRV as irrigation schemes often need rehabilitation because of land levelling problems, poor conditions of irrigation canals and inadequate land preparation. These latter operations are typically carried out by service providers with variable quality and punctuality. Our evidence suggests that the more farmers rely on those services, the more they are exposed to inefficiency. As those services are typically conducted collectively at the level of the irrigation scheme, better quality control should be carried out at the village level. This will require organizational innovation in order to optimize collective co-ordination processes (Le Gal and Papy 1998; Poussin et al. 2006).

Fertilizers are robustly found to be the single most important source of productivity, boosting both productivity and TE levels. Nevertheless, despite the rice integrated crop management (RICM) recommendations from the Africa Rice Center (WARDA/SAED 2001) and despite the fact that fertilizer costs have been halved since 2004 thanks to a 50 % government subsidy, diammoniumphosphate (DAP) fertilizer is still being underused on irrigated rice farms in the SRV. According to our surveys, the main reasons for this are the frequent breakdowns of fertilizer supply owing to institutional imperfections—the major national fertilizer factory is largely state-owned—and rising energy costs in the input market. These findings emphasize the importance of creating a stable institutional environment providing timely access to sufficient supplies of fertilizers for use in irrigated rice production in the SRV.

Our evidence suggests that R&D efforts have positively affected TE levels in the SRV. Examples are the use of improved Sahel varieties, the ASI thresher and compliance with the prescribed RICM sowing recommendations. The importance of agricultural R&D investment is well known in the rice sector; 47 % of the global R&D payoffs of the CGIAR, for instance, have been attributed to rice breeding (Raitzer and Kelley 2008) and, in turn, 29 % of the returns

from rice genetic enhancements in West Africa, in particular, were attributable to the CGIAR (Dalton and Guei 2003). Tollens et al.'s (2013) meta-analysis suggests a high median rate of return of 68 % to rice genetic improvement R&D in West and Central Africa. The high returns suggest that there is still underinvestment in R&D in the rice sector. However, a precondition to success in genetic improvement is the availability of quality seed and a functional seed sector. Farmers in the SRV often complain about the low quality (low germination rates) of seed which prevents them from sowing at optimal seed rates (de Mey et al. 2012). Our data does not show any evidence for an efficiency advantage among farmers using certified seed (Table 5). The existence of asymmetric information in the purchase of certified seed urges better control of quality and involvement of farm organizations in the seed production process (Poussin et al. 2003; Seck 2011).

Besides their role in boosting TE levels, the R&D results described above directly contribute to the objectives of the GOANA program by improving the conditions for double cropping and, hence, temporal extension of rice irrigation schemes. Short and medium duration Sahel varieties decrease the length of the growing cycle; the RICM recommendations ensure timely sowing; and the ASI thresher saves labour and time during harvesting. All these factors contribute to a widening of the timing window for double cropping and enable better planning of the agricultural season. However, Krupnik et al. (2012) observed in the SRV that although many farmers are aware of recommended management practices, none of them fully implement them in their fields. Limited adoption of available improved technologies is symptomatic of the larger region (Seck 2011) and suggests that more investment is needed in extension.

Finally, our surveys point out that bird control can be seen as a public good because control practices, carried out by one farmer, have consequences for neighbouring farmers. If one farmer scares birds from his field, these birds are only displaced to adjacent fields and unless all farmers regionally coordinate their bird control practices, damage will only be shifted among farmers. This public good-character of bird control underlines the importance of government intervention. The role of the government is to take local population control measures to relieve elevated bird pressure. Providing efficient bird control services to the farmers can be seen as an important step for increasing domestic rice production and achieving the national goals of self-sufficiency, increased food security and reduced poverty (de Mey et al. 2012).

Acknowledgments Financing from the European Union is gratefully acknowledged. This research has been made possible thanks to the valuable input of our partners SAED (*Société d'Aménagement et d'Exploitation des terres du Delta et des vallées du fleuve Sénégal et de la Falémé*) and UJAK (*Union des Jeunes Agriculteurs de Koyli-Wirnde*) in the SRV. We thank the editor and three anonymous reviewers for their constructive comments that greatly improved this manuscript.

References

- Africa Rice Center (WARDA). (2007). *Africa Rice Trends: overview of recent developments in the sub-Saharan Africa rice sector*. Cotonou, Benin: Africa Rice Center (WARDA).
- AfricaRice (2012). Améliorer la compétitivité des chaînes de valeur riz en Afrique de l'Ouest. Projet Fondation Syngenta pour une agriculture durable, Rapport annuel.
- Ahmad, M., & Bravo-Ureta, B. E. (1995). An econometric decomposition of dairy output growth. *American Journal of Agricultural Economics*, 77(4), 914–921.
- Ahmad, M., & Bravo-Ureta, B. E. (1996). Technical efficiency measures for dairy farms using panel data: a comparison of alternative model specifications. *Journal of Productivity Analysis*, 7(4), 399–415.
- Alvarez, A., & Arias, C. (2004). Technical efficiency and farm size: a conditional analysis. *Agricultural Economics*, 30(3), 241–250.
- Amara, N., Traore, N., Landry, R., & Romain, R. (1999). Technical efficiency and farmers' attitudes toward technological innovation: the case of the potato farmers in Quebec. *Canadian Journal of Agricultural Economics*, 47(1), 31–43.
- Baltagi, B. H. (2005). *Econometric analysis of panel data* (3rd ed.). West Sussex, England: John Wiley & Sons Ltd.
- Bravo-Ureta, B. E., & Pinheiro, A. E. (1993). Efficiency analysis of developing country agriculture: a review of the frontier function literature. *Agricultural and Resource Economics Review*, 22(1), 82–101.
- Bravo-Ureta, B. E., & Pinheiro, A. E. (1997). Technical, economic, and allocative efficiency in peasant farming: evidence from the Dominican Republic. *The Developing Economies*, 35(1), 48–67.
- Brüntrup, M., Nguyen, T., & Kaps, C. (2006). The rice market in Senegal. *Agriculture & Rural Development*, 1, 22–25.
- Coelli, T. J. (1996). A guide to FRONTIER Version 4.1: a computer program for stochastic frontier production and cost function estimation. CEPA Working Papers n° 96/7.
- Coelli, T. J., Prasada Rao, D. S., O'Donnell, C. J., & Battese, G. E. (2005). *An introduction to efficiency and productivity analysis* (2nd ed.). Boston: Kluwer Academic Publishers.
- Cornwell, C., Schmidt, P., & Sickles, R. C. (1990). Production frontiers with cross-sectional and time-series variation in efficiency levels. *Journal of Econometrics*, 46(1–2), 185–200.
- Dalton, T. J., & Guei, R. G. (2003). Productivity gains from rice genetic enhancements in West Africa: countries and ecologies. *World Development*, 31(2), 359–374.
- de Mey, Y., Demont, M., & Diagne, M. (2012). Estimating bird damage to rice in Africa: evidence from the Senegal River Valley. *Journal of Agricultural Economics*, 63(1), 175–200.
- Defoer, T., Wopereis, M. C. S., Jones, M. P., Lançon, F., Erenstein, O., & Guei, R. (2004). Challenges and technical opportunities for rice-based production systems for food security and poverty alleviation in sub-Saharan Africa. FAO Rice Conference, 12–13 February.
- Demont, M., & Rizzotto, A. C. (2012). Policy sequencing and the development of rice value chains in Senegal. *Development Policy Review*, 30(4), 451–472.
- Demont, M., Rodenburg, J., Diagne, M., & Diallo, S. (2009). Ex ante impact assessment of herbicide resistant rice in the Sahel. *Crop Protection*, 28(9), 728–736.
- Demont, M., Rutsaert, P., Ndour, M., & Verbeke, W. (2013a). Reversing urban bias in african rice markets: Evidence from Senegal. *World Development*, in press.
- Demont, M., Rutsaert, P., Ndour, M., Verbeke, W., Seck, P. A., & Tollens, E. (2013b). “Experimental auctions, collective induction and choice shift: Willingness-to-pay for rice quality in Senegal.” *European Review of Agricultural Economics*, in press.
- Dingkuhn, M. (1997). Characterizing irrigated rice environments using the rice phenology model RIDEV. In K. M. Miezán, M. C. S. Wopereis, M. Dingkuhn, & T. F. Randolph (Eds.), *Irrigated rice in the Sahel: prospects for sustainable development* (pp. 343–360). Saint Louis, Senegal: West Africa Rice Development Association (WARDA).
- Dingkuhn, M., & Sow, A. (1997). Potential yields of irrigated rice in the Sahel. In K. M. Miezán, M. C. S. Wopereis, M. Dingkuhn, & T. F. Randolph (Eds.), *Irrigated rice in the Sahel: prospects for sustainable development* (pp. 361–379). Saint Louis, Senegal: West Africa Rice Development Association (WARDA).
- Doss, C. R. (2006). Analyzing technology adoption using microstudies: limitations, challenges, and opportunities for improvement. *Agricultural Economics*, 34(3), 207–219.
- Fall, A. (2005). Impact économique de la recherche rizicole au Sénégal et en Mauritanie. *Agronomie Africaine*, 5, 53–62.
- Fan, S. G. (1991). Effects of technological change and institutional reform on production growth in Chinese agriculture. *American Journal of Agricultural Economics*, 73(2), 266–275.
- FAO (1997). Irrigation potential in Africa: a basin approach. <http://www.fao.org/docrep/W4347E/W4347E00.htm>.
- FAO. (2009). *FAO rice price update. Commodity markets, policy analysis and projections service, trade and markets division*. Rome: Food and Agriculture Organization of the United Nations (FAO).
- Fisher, M. G., Masters, W. A., & Sidibe, M. (2001). Technical change in Senegal's irrigated rice sector: impact assessment under uncertainty. *Agricultural Economics*, 24(2), 179–197.
- Fulginiti, L. E., & Perrin, R. K. (1998). Agricultural productivity in developing countries. *Agricultural Economics*, 19(1–2), 45–51.
- Gergely, N., & Baris, P. (2009). *Etude sur la compétitivité du riz de la Vallée du Fleuve Sénégal (VFS) sur les marchés nationaux et régionaux*. Paris, France: Agence Française de Développement (AFD).
- Good, D. H., Nadiri, M. I., Roller, L.-H., & Sicles, R. C. (1993). Efficiency and productivity growth comparisons of European and U.S. air carriers: a first look at the data. *Journal of Productivity Analysis*, 4(1–2), 115–125.
- Greene, W. H. (2002). *Econometric analysis* (5th ed.). Prentice Hall.
- Hoch, I. (1976). Returns to scale in farming: further evidence. *American Journal of Agricultural Economics*, 58(4), 745–749.
- Hossain, M. (2007). Where now for the global rice market? *Rice Today*, 6(4), 37.
- Jayne, T. S., Yamano, T., Weber, M. T., Tschirley, D., Rui, B. F., Chapoto, A., & Zulu, B. (2003). Smallholder income and land distribution in Africa: implications for poverty reduction strategies. *Food Policy*, 28(3), 253–275.
- Kalirajan, K. P., & Shand, R. T. (1999). Frontier production functions and technical efficiency measures. *Journal of Economic Surveys*, 13(2), 149–172.
- Kebbeh, M., & Miézan, K. M. (2003). Ex-ante evaluation of integrated crop management options for irrigated rice production in the Senegal River Valley. *Field Crops Research*, 81(2–3), 87–94.
- Krupnik, T. J., Shennan, C., Settle, W. H., Demont, M., Ndiaye, A. B., & Rodenburg, J. (2012). Improving irrigated rice production in the Senegal River Valley through experiential learning and innovation. *Agricultural Systems*, 109, 101–112.
- Kumbhakar, S. C., Heshmati, A., & Hjalmarsson, L. (1999). Parametric approaches to productivity measurement: a comparison among alternative models. *The Scandinavian Journal of Economics*, 101(3), 405–424.
- Kuosmanen, T., Pemsil, D., & Wesseler, J. (2006). Specification and estimation of production functions involving damage control inputs: a two-stage, semiparametric approach. *American Journal of Agricultural Economics*, 88(2), 499–511.
- Larson, D. F., Otsuka, K., Kajisa K., Estudillo, J. P., & Diagne A. (2010). Can Africa replicate Asia's green revolution in rice? Policy Research Working Paper n° 5478, The World Bank.
- Le Gal, P. Y., & Papy, F. (1998). Co-ordination processes in a collectively managed cropping system: double cropping of irrigated rice in Senegal. *Agricultural Systems*, 57(2), 135–159.

- Lichtenberg, E., & Zilberman D. (1986). The econometrics of damage control: why specification matters. *American Journal of Agricultural Economics*, 68(2), 261–273.
- Maddala, G. S. (2009). *A note on the form of production function and productivity. Measurement and interpretation of productivity* (pp. 309–317). Washington, D.C: National Research Council, National Academy of Sciences.
- MAE. (2008). *Programme national d'autosuffisance en riz à l'horizon 2015: document introductif au Conseil Interministeriel du 4 janvier 2008*. Dakar, Senegal: Ministère de l'Agriculture et de L'Elevage.
- McDonald, J. F., & Moffitt, R. A. (1980). The uses of Tobit model. *The Review of Econometrics and Statistics*, 62(2), 318–321.
- Mohapatra, S. (2011). Quality matters. *Rice Today*, 10(1), 36–37.
- Moseley, W. G., Carney, J., & Becker, L. (2010). Neoliberal policy, rural livelihoods, and urban food security in West Africa: a comparative study of The Gambia, Côte d'Ivoire, and Mali. *Proceedings of the National Academy of Sciences USA*, 107(13), 5774–5779.
- Mundlak, Y. (1978). Pooling of time-series and cross-section data. *Econometrica*, 46(1), 69–85.
- Murillo-Zamorano, L. R. (2004). Economic efficiency and frontier techniques. *Journal of Economic Surveys*, 18(1), 33–77.
- Poussin, J. C., Wopereis, M. C. S., Debouzie, D., & Maeght, J. L. (2003). Determinants of irrigated rice yield in the Senegal River valley. *European Journal of Agronomy*, 19(2), 341–356.
- Poussin, J. C., Diallo, Y., & Legoupil, J. C. (2006). Improved collective decision-making in action for irrigated rice farmers in the Senegal River Valley. *Agricultural Systems*, 89(2–3), 299–323.
- Raitzer, D. A., & Kelley, T. G. (2008). Benefit-cost meta-analysis of investment in the International Agricultural Research Centers of the CGIAR. *Agricultural Systems*, 96(1–3), 108–123.
- Randolph, T. F. (1997). Rice demand in the Sahel. In K. M. Miezán, M. C. S. Wopereis, M. Dingkuhn, J. Deckers, & T. F. Randolph (Eds.), *Irrigated rice in the Sahel: prospects for sustainable development* (pp. 71–88). Dakar, Senegal: West Africa Rice Development Association (WARDA).
- Reardon, T. (1993). Cereals demand in the Sahel and potential impacts of regional cereals protection. *World Development*, 21(1), 17–35.
- Reardon, T., Dione, J., Adesina, A., & Tefft, J. (1997). Rice in West Africa before and after CFA franc devaluation: focus on CILSS countries. In Miezán, K. M., Wopereis, M. C. S., Dingkuhn, M., & Randolph, T. F. (Eds.), *Irrigated rice in the Sahel: Prospects for sustainable development* (pp. 137–158).
- Rodenburg, J., & Johnson, D. E. (2009). Weed management in rice-based cropping systems in Africa. *Advances in Agronomy*, 103, 149–218.
- Romain, R., & Lambert, R. (1995). Efficacité technique et coûts de production dans les secteurs laitiers du Québec et de l'Ontario. *Canadian Journal of Agricultural Economics*, 47(1), 31–43.
- SAED. (2007). *Superficies et productions de riz dans la Vallée du Fleuve Sénégal entre 1990 et 2006*. Saint Louis, Sénégal: SAED/DDAR/CSE.
- SAED. (2008). *Quelles stratégies pour réussir la GOANA?* Saint Louis, Sénégal: SAED.
- SAED. (2012). *Rice production statistics in the Senegal River Valley*. Saint Louis, Senegal: SAED DataBase SAED.
- Schmidt, P., & Sickles, R. C. (1984). Production frontiers and panel data. *Journal of Business & Economic Statistics*, 2(4), 367–374.
- Seck, P. A. (2011). Feeding the world in 2050. *Rice Today*, 10(4), 12–13.
- Seck, P. A., Tollens, E., Wopereis, M. C. S., Diagne, A., & Bamba, I. (2010). Rising trends and variability of rice prices: threats and opportunities for sub-Saharan Africa. *Food Policy*, 35(5), 403–411.
- Sherlund, S. M., Barrett C. B., & Adesina A. A. (2002). Smallholder technical efficiency controlling for environmental production conditions. *Journal of Development Economics*, 69(1), 85–101.
- Tardif-Douglin, D., & Diouf, A. (1998). La consommation du riz et les effets des réformes du secteur riz au Sénégal. PASR/APAP, rapport n° 15, Ministère de l'Agriculture, République du Sénégal, Dakar.
- Tauer, L. W. (1993). Short-run and long-run efficiencies of New York dairy farms. *Agricultural and Resource Economics Review*, 22(1), 1–9.
- Tollens, E., Demont, M., Sié, M., Diagne, A., Saito, K., & Wopereis, M. C. S. (2013). Forty years of rice R&D: achievements and lessons learned. In M. C. S. Wopereis, D. Johnson, T. Horie, E. Tollens, & A. Jalloh (Eds.), *Realizing Africa's rice promise Wallingford*. UK: CABI Publishing.
- USDA (2008). Senegal grain and feed update: West Africa regional rice annual 2008. GAIN Report n° SG8009.
- USDA (2011a). Nigeria: Grain and feed annual. GAIN Report NI11015: USDA Foreign Agricultural Service .
- USDA (2011b). Production, supply and distribution online. <http://www.fas.usda.gov/psdonline>.
- USDA (2012). 2012 West Africa: rice annual. GAIN Report: USDA Foreign Agricultural Service.
- Wang, H.-J., & Schmidt, P. (2002). One-step and two-step estimation of the effects of exogenous variables on technical efficiency levels. *Journal of Productivity Analysis*, 18(2), 129–144.
- WARDA/SAED (2001). *Manual pratique de riziculture irriguée dans la vallée du fleuve Sénégal*. Saint-Louis, Senegal: Africa Rice Center (WARDA) and Société Nationale d'Aménagement et d'Exploitation des terres du Delta du fleuve Sénégal et des vallées du fleuve Sénégal et de la Falémé (SAED).
- Wooldridge, J. M. (2001). *The single-equation linear model and OLS estimation. Econometric analysis of cross section and panel data* (pp. 49–81). London, England: The MIT Press.
- Wopereis, M. C. S., Donovan, C., Nebie, B., Guindo, D., & N'Diaye, M. K. (1999). Soil fertility management in irrigated rice systems in the Sahel and Savanna regions of West Africa. Part I. Agronomic analysis. *Field Crops Research*, 61(2), 125–145.
- World Bank (2006). Republic of Senegal, joint IDA-IMF staff advisory note of the second poverty reduction strategy paper. n° 38131-SN, World Bank, Washington.
- World Bank. (2008). *World development report 2008*. Washington, DC: The World Bank.
- Zhengfei, G., Oude Lansink A., van Ittersum M., & Wossink A. (2006). Integrating agronomic principles into production function specification: a dichotomy of growth inputs and facilitating inputs. *American Journal of Agricultural Economics*, 88(1), 203–214.



Mandiaye Diagne is Senegalese and is currently working at the Africa Rice Center (AfricaRice) as agricultural economist and researcher in the programme Policy, Impact Assessment and Innovation Systems. He is currently based at the Sahel Regional Station of AfricaRice in Saint-Louis, Senegal. His areas of specialization and interest include adoption and impact assessment of agricultural technologies, trade modeling and food security

issues, as well as productivity and policy analysis. He has a vast experience in research collaborative activities between International Agricultural Research Centers (IARC) and National Agricultural Research Systems (NARS). In 2010, Mandiaye was awarded a “Sandwich” Scholarship by the DAAD (German Academic Exchange Service) as visiting Scientist at the Food Security Center (University of Hohenheim, Stuttgart, Germany) to complete one part of his PhD work which he defended in 2011 at the University of Gaston Berger in Saint Louis, Senegal.



Matty Demont is a European agricultural economist currently working at the Africa Rice Center (AfricaRice) as Senior Value Chain Economist. He is a permanent board member of the International Consortium of Applied Bioeconomy Research (ICABR). His early work (1996–1999) included research on food marketing and farming systems in Côte d'Ivoire, for which he received the Xavier Bernard Award by the Academy of Agriculture of France in 1999. Before taking up

his current position at AfricaRice, he conducted his PhD and Post-doc research (1999–2007) at the University of Leuven, Belgium on the impact of biotechnology innovations and the EU coexistence policy on European agriculture. He has published widely in refereed journals, books and magazines and has contributed to a vast array of international conferences and workshops. Matty pioneered rice value chain research in Africa by experimenting as to how urban bias can be reversed in African rice markets. To this end, he conducted 13 experimental auctions throughout Africa involving more than 1,700 women which has provided unique insights into the bottlenecks in rice value chain upgrading. In 2012, his work was awarded the T.W. Schultz Award by the International Association of Agricultural Economists and the Louis Malassis International Scientific Prize by Agropolis Fondation, France.



Papa Abdoulaye Seck is a specialist in agricultural policy analysis and strategy. He is a permanent member of the Senegal Academy of Sciences and has the rank of Director of Research. He is on the advisory board of the Strategic Orientation Council of Agreenium, France and Executive Committee of GFAR. He is currently Director General of Africa Rice Center (AfricaRice), one of the 15 international Centers of the CGIAR Consortium. Before

this, he was Director General of the Senegal Agricultural Research Institute and Technical Advisor to the Prime Minister of Senegal and

Chair of FARA. He holds a PhD in Agricultural Economics, Policies and Analysis and a degree in Computer Science. He has received the title of Chevalier in the Order of Agricultural Merit of France, Certificate of Recognition from FARA, Medal of Honor from CORAF/WECARD, Award of Recognition from Mali, the title of the Chevalier in the National Order of Lion and Officer in the Order of Merit of Senegal. He is co-laureate of the 2012 TW Schultz Prize presented by the International Association of Agricultural Economists. He has authored or co-authored 80 publications, including articles, papers in international conferences with scientific committees, books and forewords for more than 10 books.



Adama Diaw Senegalese citizen is a well-known macroeconomist and Professor of economics and former Dean of the Faculty of Economics with the University of Gaston Berger, Saint-Louis, Senegal. His area of research is on monetary and financial aspects of development economics. He holds a PHD in development economics from the University of Auvergne at Clermont-Ferrand in France. He has published widely in refereed journals and attended a lot of

conferences and workshops around the world. He is a visiting professor in many universities in the sub-region and in France.

Prof Diaw is a member of the Scientific Committee of some well-known academic journals including *Revue d'Economie du Développement*, *Revue Economie et Gestion*, *Revue Economique et Monétaire* and *Revue Région et Développement*. He has also conducted a lot of consultancy work for international organizations like the World Bank, the West African Monetary Agency, the Central Bank of West African States (BCEAO) and the UNDP.

He is currently Director of the Graduate and post-Graduate School of Social Sciences and President of the Scientific Committee of the Direction of forecasting and Economic Studies, Ministry of Finances of Senegal and member of the National Credit Council of the BCEAO. He is also member of the Academic Board of the Graduate Program of the African Economic Consortium (AERC) located in Nairobi, Kenya.