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Profitable and Sustainable Fertilizer-Management Option in Double Cropping of Irrigated Rice in Senegal River Valley

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Abstract

One of the main factors limiting the yield and productivity of irrigated rice in the Sahel of West Africa is the high cost of fertilizers and inefficient use of nutrients in the cropping systems. A two-year experiment was conducted over four consecutive seasons at Ndiaye (16°11'N, 16°15'W) and Fanaye (16°32'N, 15°11'W) along the Senegal River Valley to investigate alternative fertilizer management options in the double cropping system of rice. Eight fertilizer management options (FMO) were compared to the recommended seasonal application of NPK fertilizer based on yield data, the value-cost ratio (V/C) and the sustainabily of the recommendation. Rice yields increased from 2.5 t/ha without fertilizer application to 8 t/ha under the nine FMOs, which produced similar yields each season at both sites. The V/Cs of the recommended NPK fertilizer (applied each season) varied from 2.3 to 3.7. The V/Cs of FMO that supplied NPK during the hot dry season (HDS) and N during the wet season (WS), or conversely (NPK-N) varied from 3.2 to 5.7. The V/Cs of NPK-NP varied from 2.4 to 4.3. The V/Cs of NPK-NK varied from 2.4 to 4.4. The highest V/Cs ratios (5.2 to 6.3) were obtained by FMOs that supplied NP during the HDS and N during the WS, or conversely. It is concluded that when soil P-Bray1 is above 7 mg P ha^{-1}, FMOs that supply NPK fertilizer in one season and only N fertilizer in the following season could reduce the cost of fertilization by 26% and improve rice productivity for sustainable management of the double cropping system of rice in the Senegal River Valley.

Keywords: nutrients, fertilizer, soil, rice, cropping systems

Abbreviations: SRV=Senegal River Valley, HDS = Hot Dry Season, WS=Wet Season, FMO = Fertilizer management option, V/C=Value Cost ratio

1. Introduction

The per capita consumption of rice (*Oryza sativa)* in the Sahelian countries of West Africa in 2003 was estimated at 43 kg (FAO-stat, 2009). In 2035, more than 30 million tons of rice will be needed by Africa, an increase of 130% from the demand in 2010 (Seck, Diagne, Mohanty, & Wopereis, 2012). Despite a long tradition of rice cultivation, local production is lower than the demand for rice in every country in West Africa. In general, local production supplies less than 50% of the rice needs. Consequently, more than 50% of the rice consumed is imported – the cost of importation in 2005 was US$ 1.1 billion (FAO-stat, 2009). Enormous efforts and resources have been invested into the development of irrigation schemes to enhance irrigated rice production as a means of promoting food security. The adoption of structural adjustment and market liberalization policies, with support from the World Bank and the International Monetary Fund, has further enhanced the potential and the environment for developing the rice sector in Africa. In Senegal, for instance, rice production in irrigated schemes is one of the most important activities, with 50 000 ha being cultivated (SAED, 2007). Rice is becoming the most important cereal crop in many inland valleys of West Africa and is cultivated as a staple food by farmers in the small inland valleys, or as a cash crop in many irrigated schemes.

However, low productivity remains a limiting factor for improving global rice production. While the simulated potential yield of irrigated rice in the Senegal River Valley (SRV) is 8-12 t/ha (Dingkuhn & Sow, 1997), the average yields in farmers' fields vary from 4 to 6 tons ha^{-1} (Haefele, Wopereis & Wiechmann, 2002; Kebbeh & Miezan, 2003). There is scope for increasing rice yields with the sustainable intensification of the existing cropping systems using efficient management of inputs, particularly seeds, water and fertilizers. AfricaRice and its National Agricultural Research Systems (NARS) partners have developed and released several high yielding rice varieties in many countries. However, high yielding varieties require good management of fertilizers. The use of fertilizers in sub-Saharan Africa (SSA) is known to be limited by the financial means and risk-taking capacity of farmers, as well as the poor and expensive fertilizer distribution systems (Zapata & Roy, 2004). AfricaRice has also developed many integrated crop management (ICM) technologies that focus on fertilizer efficiency improvement, weed management and varieties for increasing efficiency and productivity (Wopereis, Donovan, Nebié, Guindo, & N'Diaye, 1999; Haefele, 2001; Haefele *et al*., 2002; Haefele, Wopereis, Ndiaye, & Kropff, 2003). Deficiencies in nitrogen (N) and phosphorus (P) are the main limiting factors for rice (Haefele *et al*., 2002; Bado, De Vries, Haefele, Marco, & Ndiaye, 2007). The standard approach for developing fertilizer recommendations is based on the selection of a soil test, calibration of the soil test levels with crop response to added nutrients, and identification of response categories. New modeling approaches using crop simulation models or decision-support tools have contributed greatly to the development of site-specific fertilization recommendations. For example, Haefele *et al*. (2003) developed a framework for improving fertilizer recommendations for rice. This framework combines the rice yield model ORYZAS developed by (Dingkuhn & Sow, 1997) to simulate the response of rice to extreme temperatures in Sahel, a simplified version of QUEFTS called FERRIZ , and the field survey data in order to develop fertilizer recommendations for irrigated rice.

While the rice-based systems are becoming more and more intensified, these approaches for development of fertilizer recommendations have not considered the long-term effect of fertilizer use. While many farmers grow two rice crops (during the wet and hot dry seasons) per year, fertilizer recommendations and ICM technologies are usually developed for each season. Fertilizer recommendations per season do not consider the possible cumulative effect of fertilizer applied during the preceding season of the same year. The capacity of the soil to supply a specific nutrient can be modified over time, depending on the quantities of nutrient supplied by fertilizers and nutrient uptake by the crop. For example, a long-term application of P fertilizers can increase soil extractable P over time as a consequence of low P uptake compared to P supplied by fertilizer. Knowledge of the short- and long-term dynamics of soil P under different fertilizer treatments is important for the sustainable management of cropping systems (Zhang *et al*., 2006). Various studies have shown how P fertilizer additions primarily affected labile and acid-soluble inorganic P fractions in acid soils of the tropics under upland rice cropping and P transformations in lowland rice-cropping systems that undergo alternate wetting and drying cycles (Dobermann, George, & Thevs, 2002; Zhang *et al*., 2006). Flooding, in general, leads to an initial increase in the availability of P to plants due to reductive dissolution of iron oxides and faster P diffusion to the roots, whereas subsequent soil drainage and drying periods often result in impaired P availability, particularly with regard to seasonal soil P dynamics (Zhang *et al*., 2006). Using soil data from a long-term fertility experiment (LTFE), Bado, Aw and Ndiaye (2010) pointed out that although the original soil extractable P is very low in many cases, soil extractable P can significantly increase over time with continuous applications (two application per year) of the recommended dose of fertilizers. A critical level of 9 mg P kg^{-1} (Bray1 P) or 17 mg P kg-1 (Olsen P) was determined for rice production in the SRV (Bado *et al*., 2007) and P fertilizer applications are recommended when soil extractable P decreases below this critical level. Otherwise, P remained a limiting factor for increasing rice yield when the soil extractable decreases below this critical level. Phosphorous fertilizer should be applied when the soil cannot supply more than these values of extractable P. Concerning soil-K, many authors revealed that most of irrigated lowland valleys in the Sahel have considerable soil K reserves (Buri, Ishida, Kubota, Masunaga, & Wakatsuki, 1999; Wopereis *et al*., 1999; Haefele, Wopereis, Schloebohm, & Wiechmann, 2004). Besides, Bado *et al*. (2010) showed that soil exchangeable-K was maintained or increasead with the seasonal application of 50 kg K ha^{-1} after consecutive 18 years of rice cropping in the Senegal River Valley.

Some management strategies were suggested for rice double cropping system. Considering its mobility, nitrogen needs to be applied each season at different rice growth stages whereas P and K do not need to be applied each season because of the gradual accumulation of these nutrients (Bado *et al*., 2010).

The main objective of this study was to clarify that alternative fertilizer management options using one application of P and K fertilizers per year for the two cropping seasons of rice, combined with the recommended doses of N fertilizer for each season can reduce the costs of fertilization in rice double cropping systems. The main goal was to improve the productivity of the intensive double cropping system of irrigated rice by using a single management option of fertilizer for the two cropping seasons, instead of one recommendation for each season.

2. Material and Methods

2.1. Experimental Sites

The study was conducted at two sites in the SRV (Senegal, West Africa) during four successive cropping seasons of irrigated rice in two years. The experimental sites are located at the two Africa Rice Center (AfricaRice) research stations at Ndiaye (16^{o} 11’ N, 16^{o} 15’W) and Fanaye (16^{o} 32’ N, 15^{o} 11’W). Climate at both sites is typically Sahelian: a 9-month dry period followed by a short wet season, and large annual amplitudes in temperature (Figure 1). Between March and July, solar radiation and maximum temperatures are higher at Fanaye than at Ndiaye. In general, rice production takes place twice a year, from February to June in the hot dry season (HDS), and from August to November in the wet season (WS).

The experimental station at Ndiaye is located in a depression along one of the branches of the Senegal River (Haefele, 2001). Deposits of marine origin in the sub-soil result in a saline ground water table of 20 dS m-1 or more (Ceuppens, 2000), which is 0.9– 0.4 m below the soil surface. Following the FAO soil classification (FAO, 2006), the soil is characterized as an orthothionic Gleysol, with a clayey structure that contains 40–54% clay, composed of smectite and kaolinite (Haefele 2001). Average percolation rate of this soil was estimated at 2.8 mm d^{-1} (Haefele, 2001).

The Fanaye station has a deep ground water table, constantly below 3.0 m. No inherent salinity was found at this site. The soil type is characterized as an eutric Vertisol (FAO soil classification), where clay content was higher (45% and 65%), composed of kaolinite and smectite minerals (Samba-Diène, 1998; Haefele, 2001) with less porosity and bulk density than the soil of Ndiaye. The percolation rate was estimated at 2.0 mm d^{-1} at the same site (Haefele, 2001).

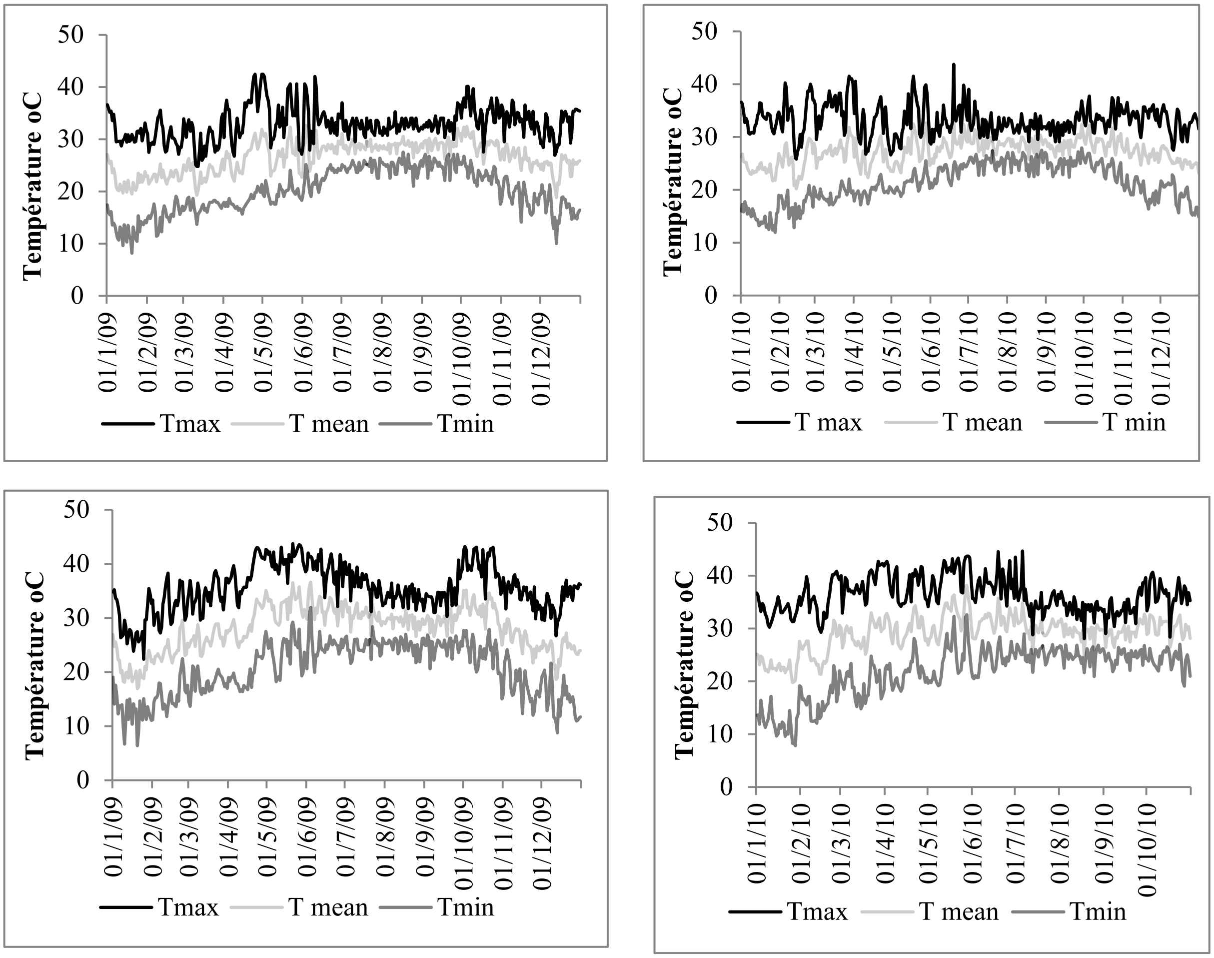

Figure 1. Variation of temperature at Ndiaye (delta) and Fanaye (middle valley) during the two years (2009 to 2010) of the agronomic experiment

2.2. Agronomic Experiments

Field agronomic experiments were conducted during four consecutive seasons (HDS and WS) in two years (2009-2010) at the two sites. Each field experiment had ten fertilizer treatments and four replications in a randomized complete block design. The ten fertilizer treatments included the common practice (current recommended fertilizers) and one absolute control without any fertilizer application (Table 1). The FMOs were developed considering that N fertilizer needs to be applied each season while P, K or both P and K nutrients could be applied only once per year. The current recommendation is to apply NPK fertilizer at the rate of 120 kg N ha^{-1}, 26 kg P ha^{-1} and 50 kg K ha^{-1} each season (FMO_1). This rate was used as a reference since it is used by most farmers with slight modifications on the rate of N (120- 180 kg N ha^{-1}, depending on the season.

The management options FMO_2 (NPK-N) and FMO_3 (N-NPK) supplied the recommended NPK fertilizer only during the HDS (FMO_2) or during the wet season (FMO_3). Only N fertilizer was applied during the WS (FMO_2) or during the HDS (FMO_3).

FMO_4 (NPK-NP) and FMO_5 (NP-NPK) supplied the recommended NPK fertilizer during the HDS (FMO_4) or during the WS (FMO_5). NP fertilizer (without K) was applied during the WS (FMO_4) or during the HDS (FMO_5).

FMO_6 (NPK-NK) and FMO_7 (NK-NPK) supplied the recommended NPK fertilizer during the HDS (FMO_6) or during the WS (FMO_7). NK fertilizer (without P) was applied during the WS (FMO_6) or during the HDS (FMO_7).

FMO_8 (NP-N) and FMO_9 (N-NP) supplied NP fertilizer during the HDS (FMO_8) or during the WS (FMO_9). N fertilizer alone was applied during the WS (FMO_8) or during the HDS (FMO_9).

Table 1. Treatments of Fertilizer Management Option (FMO) tested over the Hot Dry Season (HDS) and Wet Season (WS) on the two sites (Ndiaye and Fanaye) during the two years of experimentation (2009 to 2010)

	Year 2009		Year 2010	
Fertilizer Management option (FMO)	Hot Dry Season (HDS)	Wet Season (WS)	Hot Dry Season (HDS)	Wet Season (WS)
FMO_1: NPK-NPK	NPK	NPK	NPK	NPK
FMO_2: NPK-N	NPK	N	NPK	N
FMO_3: N-NPK	N	NPK	N	NPK
FMO_4: NPK-NP	NPK	NP	NPK	NP
FMO_5 NP-NPK	NP	NPK	NP	NPK
FMO_6: NPK-NK	NPK	NK	NPK	NK
FMO_7: NK-NPK	NK	NPK	NK	NPK
FMO_8: NP-N	NP	N	NP	N
FMO_9: N-NP	N	NP	N	NP
Control	0N-0P-0K	0N-0P-0K	0N-0P-0K	0N-0P-0K

Experimental plots measured 25 m^2 (5 x 5 m). Small 30 cm high dikes separated the experimental plots. Rice seedlings were transplanted at the rate of 25 hills m^{-2}. Crop management was adjusted to the farmers' practice. NPK nutrients were applied in the form of urea, triple super phosphate (TSP) and potassium chloride (KCl). TSP and KCl were applied basally before transplanting. For all fertilizer treatments, 50% N, 100% P and 100% K were broadcast at 21 days after transplanting in slim standing water. The remaining N dose was split-applied at panicle initiation (25%) and 10 days before flowering (25%). Herbicide (6 l ha^{-1} Propanyl) and manual weeding were used for weed control. Herbicide was applied once at 21 days after sowing, 1 day before the first N application; thereafter, plots were kept weed-free by manual weeding. Insecticides (Furadan) were sometimes used at 25 kg ha^{-1} for pest control at the start of tillering, maximum tillering, panicle initiation and flowering. A constant water layer of 10-15 cm was maintained during the whole cropping season to control weeds development and the harvested straw was removed from the plots every season. Rice grain yields were determined from a 4 m^2 harvest area in each plot at maturity and reported at a standard water content of 140 g water kg^{-1} fresh weight. The released variety Sahel 108, which is cropped on about 70 % of the irrigated area on the SRV and also adapted to HDS and WS (WARDA, 2000), was used at both sites.

2.3. Soil Sampling and Analyses

At both sites, the experiments were established on fields that had been under continuous flooded-rice cultivation for three seasons with a uniform application of the recommended dose of NPK fertilizer supplying 120, 26 and 50 kg ha^{-1} of N, P and K nutrient, respectively. The experimental fields were kept fallow for one season (natural fallow) before implementing the experiments. Prior to the field experiments, five sub-samples of soil were taken from topsoil (0–20 cm) from individual plots. The sub- samples were mixed thoroughly to get a composite sample, air-dried immediately after collection for 1 week. The samples were analyzed in the soil laboratory at AfricaRice. Soil pH was determined in a 1:1.25 H_2O solution and EC in a 1:5 paste. Total N was determined using the micro-Kjeldahl method for N analysis (Bremner, 1965). Soil organic C was determined using the wet digestion method (Walkley & Black, 1934). Available soil phosphorous was determined by the Bray-P1 method using the extractant 0.03 N NH4F in 0.025 N HCl (Bray & Kurtz, 1945). Soil exchangeable K (Kexch) was extracted with 1 M NH4OACc solution (Helmke & Sparks, 1996).

2.4. Statistical Analysis

The statistical analysis of the data was done using the four factors: year, site, season and fertilizer treatments (Gomez & Gamez, 1983). A one-way analysis of variance (ANOVA) was used to analyze the main effects of the four factors and their interactions using the statistical SAS software (SAS, 1995).

2.5. Profitability Analyses

The cost of fertilizer can be used to compare the different FMOs. The total cost of fertilizer and the profitability analysis of the performance of each FMO were calculated on an annual basis (for the two cropping seasons of each year). Considering the recommended NPK fertilizer usually applied by farmers as a reference (FMO_1), the 8 alternative FMOs were compared in terms of financial investment for fertilizer. A reduction of the cost of fertilizer for the tested FMO*i* (ΔC) was calculated (as a percentage) in comparison to this reference FMO_1 (Equation 1).

$$\Delta C\ (\%) = ((C\_FMO_1 - C\_FMO_i) / \text{Cost of } FMO_1) * 100 \quad (1)$$

Where C_FMO_1 and C_FMO_i are the costs of the recommended management option (FMO_1) and the cost of a studied fertilizer management option (FMO_i).

The value/cost ratio (V/C) was used to compare the performance of the FMOs as a profitabily index between revenu provided by a fertilizer rmanagement option (FMO) and the cost of fertilizer of this FMO (Crawford & Kamuanga, 1991). The V/C ratio was calculated by the variation of revenue provided by a FMO compared to that of the control treatment (without any fertilizer), divided by the cost of fertilizer that was applied to produce this revenue (Equation 2).

$$V/C = (Y_{FMOi} - Y_0) \times (P_{paddy})/(C_{FMOi}) \quad (2)$$

Y_{FMOi} and Y_0 represent the paddy yield obtained under *i* fertilizer management option (*FMOi*) and that of the absolute control treatment (without any fertilizer application), respectivelly. P_{paddy} is the price of paddy rice on the local market and C_{FMOi} is the cost of fertilizer applied under *FMOi*. Fertilizer costs were based on average 2009-2010 prices of fertilizers in the Delta and Middle valley. The prices of urea, triple super phosphate (TSP) and potassium Chloride (KCl) were 143, 340 and 450 XOF kg^{-1}, respectivelly (Dieng *et al.*, 2011). The field price of paddy rice was 100 and 110 XOF kg^{-1} at Ndiaye and Fanaye, respectively. An additional 16% of fertilizer costs were added to include transport costs, interest and labour costs for application (Donovan *et al.*, 1999).The exchange rate was US$ 1 for 490 XOF (the local currency).

3. Results and Discussion

3.1. Soil Properties

The soil of the experimental plots at Ndiaye (Delta valley) was weekly acidic ($pH/H_2O = 5.8$) with a high potential acidity (pH/KCl = 3.2). The N and C contents were low but the C/N ratio (10.3) indicated a low level of organic matter (1.24 %). At Fanaye (Middle valley), the soil was less acidic ($pH/H_2O = 6.4$) with a low potential acidity (pH/KCl = 5.1). The N and C contents were also low with a relatively high C/N ratio (14.3) due to the low level of N. The extractable P (Bray1-P) varied from 7.54 to 8.22 mg P Kg^{-1} at Fanaye and Ndiaye, respectively. Soil exchangeable K varied from 125 mg to 148 mg K Kg^{-1} at Fanaye and Ndiaye, respectively (Table 2.).

Table 2. Main characteristics of the soil at 20 cm depth in the two sites (Ndiaye in the Delta valley and Fanaye in the Middle valley) in begining of the trial

Parameters	Ndiaye	Fanaye
pH (H2O)	5.83 (0.88)	6.40 (1.02)
pH (KCl)	3.24 (0.54)	5.10 (0.72)
C (%)	0.72 (0.21)	0.57 (0.26)
N (%)	0.07 (0.02)	0.04 (0.03)
C/N ratio	10.28 (1.88)	14.25 (2.79)
OM (%)	1.24 (0.65)	0.98 (0.42)
P Bray 1 (mg kg^{-1})	8.22 (1.61)	7.54 (1.38)
K (mg kg^{-1})	148 (2.22)	125 (1.01)

*OM. Organic Matter. Standard deviation in bracket

3.2. Rice Yields

Yield data for the four seasons of the two years were analyzed for the different factors (year, season, site and fertilizer treatments) and the different interactions among factors (Table 3). Rice yields were significantly affected (*P<0.01*) by fertilizer application, site, and season. The effects of climate within seasons and years and specific characteristics of the soils of the two sites can explain the influence of site, season and year on rice yields. The influence of sites and seasons on grain yields can be explained by climatic variability (Dingkuhn & Sow, 1997; Bado *et al*., 2010). There was no interaction between fertilizer and season, indicating that the influence of seasons did not affect the differences between fertilizer treatments over seasons and conversely. However, a significant interaction (P<0.01) was observed between fertilizer and site, indicating that the efficiency of a fertilizer treatment could depend of the site where it was applied and conversely. Therefore, the effect of fertilizer treatments should be analyzed by site, taking into account the influence of site on the response of rice to the fertilizer management options.

Table 3. Analysis of variance of the effects of fertilizer treatments, sites, season and year and interactions within factors on rice grain yields during the four seasons of the two years (2009-2010)

Source of variation	DF	Mean square	F value	Probability
Fertilizer	9	68.09	37.40	0.0001
Site	1	21.76	11.95	0.0006
Season	1	36.00	19.78	0.0001
Year	1	0.40	0.22	0.6377
Fertilizer*Site	9	4.57	2.51	0.0087
Fertilizer*Season	9	2.53	1.39	0.1925
Fertilizer*Site*Season	9	2.01	1.10	0.3584
R-Square	0.69			
Coefficient of Variation	24.4			

Table 4. Rice yields and profitability analyzes on annual basis of different fertilizer management options (FMOs) during two years (2009 and 2010) in the delta (Ndiaye) and the middle valley (Fanaye)

Site	Treatments	Cost (C)	ΔC	2009				2010				Average 2009-2010			
		US$	(%)	(a)	(b)	V	V/C	(a)	(b)	V	V/C	(a)	(b)	V	V/C
Delta (Ndiaye)	FMO_1: NPK-NPK	602		15.1^{a}	8.46	1692	2.8	13.0^{a}	6.96	1392	2.3	14.0^{a}	7.7	1540	2.6
	FMO_2:NPK-N	443	26	16.1^{a}	9.48	1896	4.3	14.1^{a}	8.10	1620	3.7	15.1^{a}	8.8	1760	4.0
	FMO_3:N-NPK	443	26	15.6^{a}	8.96	1792	4.0	13.1^{a}	7.12	1424	3.2	14.3^{a}	8.04	1608	3.6
	FMO_4:NPK-NP	563	7	13.2^{ab}	6.62	1324	2.4	14.2^{a}	8.22	1644	2.9	13.7^{a}	7.42	1484	2.6
	FMO_5:NP-NPK	563	7	15.1^{a}	8.48	1696	3.0	13.4^{a}	7.36	1472	2.6	14.2^{a}	7.92	1584	2.8
	FMO_6:NPK-NK	565	6	15.2^{a}	8.56	1712	3.0	13.6^{a}	7.56	1512	2.7	14.4^{a}	8.06	1612	2.9
	FMO_7:NK-NPK	565	6	15.7^{a}	9.14	1828	3.2	12.8^{a}	6.80	1360	2.4	14.3^{a}	7.98	1596	2.8
	FMO_8:NP-N	321	47	15.4^{a}	8.8	1760	5.5	13.6^{a}	7.60	1520	4.7	14.5^{a}	8.2	1640	5.1
	FMO_9:N-NP	321	47	14.9^{a}	8.3	1660	5.2	13.3^{a}	7.30	1460	4.5	14.1^{a}	7.8	1560	4.9
	Absolute control			6.6^{b}				6.0^{b}				6.3^{b}			
Middle valley (Fanaye)	FMO_1: NPK-NPK	602		14.5^{a}	8.62	1896	3.2	16.2^{a}	10.20	2244	3.7	15.4^{a}	9.06	2070	3.4
	FMO_2:NPK-N	443	26	14.5^{a}	8.56	1883	4.3	17.0^{a}	11.00	2420	5.5	15.7^{a}	9.44	2152	4.8
	FMO_3:N-NPK	443	26	14.4^{a}	8.54	1879	4.2	17.4^{a}	11.38	2504	5.7	15.9^{a}	9.62	2192	4.9
	FMO_4:NPK-NP	563	7	14.5^{a}	8.56	1883	3.3	16.9^{a}	10.94	2407	4.3	15.7^{a}	9.4	2145	3.8
	FMO_5:NP-NPK	563	7	15.2^{a}	9.32	2050	3.6	16.5^{a}	10.52	2314	4.1	15.9^{a}	9.58	2182	3.9
	FMO_6:NPK-NK	565	6	14.0^{a}	8.12	1786	3.2	16.5^{a}	10.48	2306	4.1	15.3^{a}	8.96	2046	3.6
	FMO_7:NK-NPK	565	6	15.2^{a}	9.3	2046	3.6	17.2^{a}	11.20	2464	4.4	16.2^{a}	9.9	2255	4.0
	FMO_8:NP-N	321	47	14.1^{a}	8.2	1804	5.6	15.8^{a}	9.80	2156	6.7	14.9^{a}	8.64	1980	6.2
	FMO_9:N-NP	321	47	13.5^{a}	7.6	1672	5.2	16.8^{a}	10.80	2376	7.4	15.1^{a}	8.84	2024	6.3
	Absolute control			5.9^{b}				4.3^{b}				5.1^{b}			

Note: Yield values followed by the same letters on the same site and the same column are not significantly different ($P<0.001$) according the Fisher test. (a): annual average yield (tones ha^{-1}); (b): yield increase over Control (tones ha^{-1}). V: value of production increase by fertilizer applications ((b) × paddy price= US$0.20 and US$0.22 kg^{-1} at Ndiaye and Fanaye, respectively). C: cost of Fertilizers. Δ C (%): Reduction of fertilizer cost compared to NPK-NPK (FMO_1).

3.2.1. Ndiaye (Delta Valley)

Rice yields were relatively stable at around 3 tons ha^{-1} when fertilizer was not applied during the four seasons. However, rice yields increased significantly with the application of fertilizers during the four seasons as a consequence of nutrients supplied by fertilizers (Figure 2). The highest yields were observed for the nine FMOs during the first season (HDS) of the first year. This was probably a seasonal effect as reflected by the good yields also observed on other field experiments at this site during this season. In spite of these seasonal variations, there was no significant difference in yield between the nine FMOs during the four seasons (Figure 2).

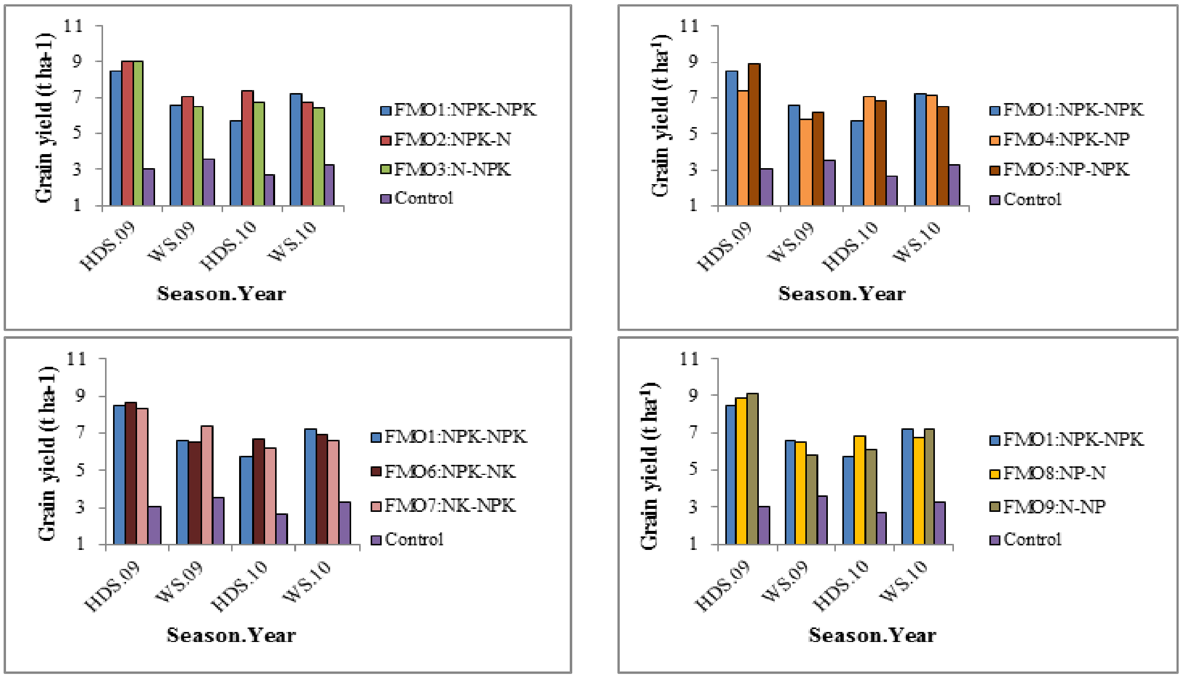

Figure 2. Effect of different fertilizer management options (FMOs) on grain yields over four consecutive seasons during two years (2009-2010) at Ndiaye. HDS 09 and HDS.10: Hot Dry Season 2009 and 2010; WS 09 an WS.10: Wet Season 2009 and 2010

The agronomic efficiencies of the FMOs can also be assessed by the average annual yields and the average yields of the four seasons as presented in Table 4. With zero fertilizer application (absolute control), mean rice yield varied from 3.3 t ha^{-1} in 2009 to 3.0 t ha^{-1} in 2010. All the nine FMOs increased rice yields but there was no significant difference between them.

3.2.2. Fanaye (Middle Valley)

With zero fertilizer application (absolute control), rice yields varied from 1 to 3 t ha^{-1}. As observed at Ndiaye, rice yields were significantly increased with the application of fertilizers during the four seasons as a consequence of nutrients supplied by fertilizers, but differences between the nine FMOs were not significant (Figure 3). The average annual yields and the average yields of the four seasons indicated that rice yields were also increased by all the nine FMOs compared to the absolute control and there was no significant difference between them, as was observed at Ndiaye. In contrast to Ndiaye, yields even declined slightly over the seasons at Fanaye.

Considering our research hypothesis, it was particularly interesting to note that all the nine FMOs produced similar yields (no significant difference) during the four cropping seasons at the two sites. Even the application of N fertilizer alone (FMO_2, FMO_3, FMO_8, and FMO_9) produced similar yields compared to the recommended NPK (FMO_1). Otherwise, N fertilizer should be applied each season but P and K nutrients could be applied in one season per year without any yield reduction.

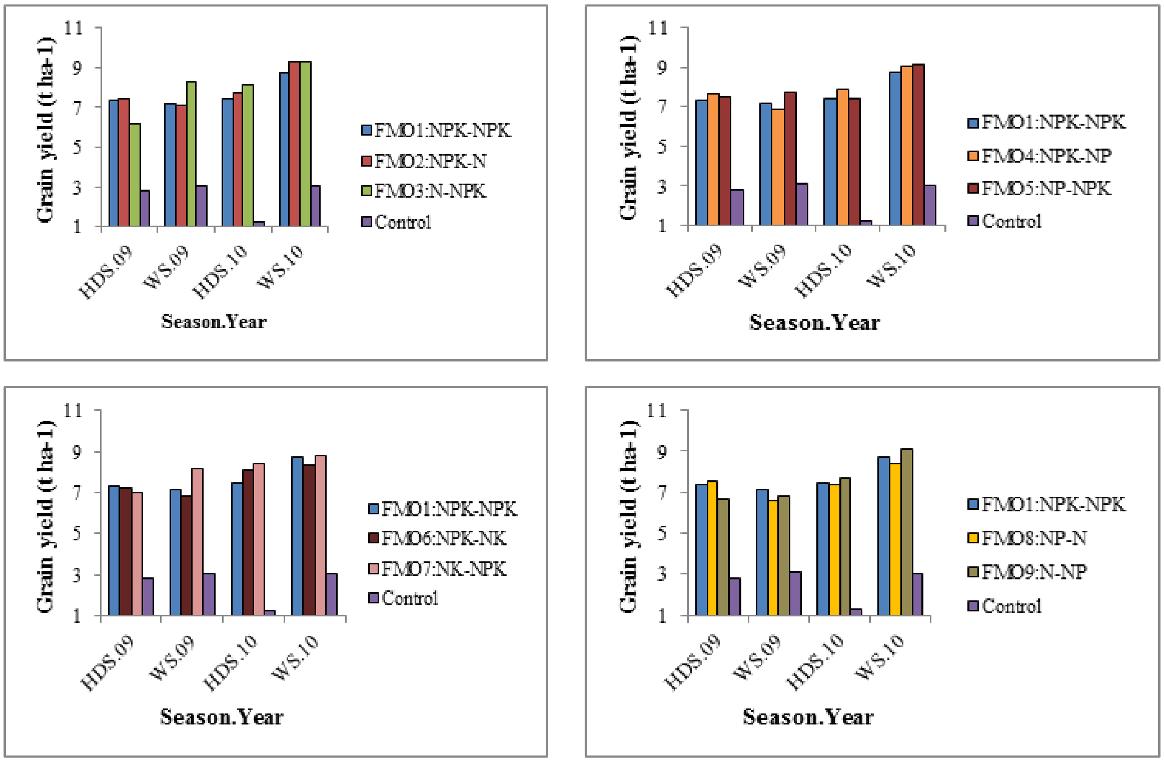

Figure 3. Effect of different fertilizer management options (FMOs) on grain yields over four consecutive seasons during two years (2009-2010) at Fanaye. HDS 09 and HDS.10: Hot Dry Season 2009 and 2010; WS 09 an WS.10: Wet Season 2009 and 2010

3.3. Profitability Analysis

The total cost of each fertilizer management option (FMOs) and the profitability analysis of its performances were calculated on an annual basis for the two cropping seasons per year (Table 4). The cost of fertilizers of the recommended NPK (FMO_1) was \$602 per year (at least \$300 per season). The costs of the eight studied FMOs were cheaper than the recommended FMO_1 and varied from \$321 to \$565. In other words, the studied FMOs reduced the cost of fertilizer by 6 to 47% compared to the recommended option (FMO_1). Management options that use only N and P fertilizers (without K fertilizer: $FMO_{8\ \mathrm{and}}$ FMO_9) were the cheaper options and the cost of fertilizer was reduced from 47% compared to FMO_1.

As a profitability index, value/cost ratios were superior to 2 units for all the FMOs at both sites during the two years, confirming the profitability of fertilizers on rice (Crawford & Kamuanga, 1991). The value/cost ratio of the recommended FMO_1 varied from 2.3 to 2.8 and from 3.0 to 3.7 at Ndiaye and Fanaye, respectively. In other words, \$1 (490 XOF) invested in fertilizer can provide a benefit of \$2.3 to 3.7. Lower value/cost ratios of NPK fertilizer (1.5 to 2.9) were reported by Segda, Haefele, Wopereis, Sedogo, and Guinko (2003) for irrigated rice in Burkina Faso (West Africa Sahel). This can be explained by the low yields at this irrigation scheme (5 t ha^{-1}) compared to those of the SRV. MFO_1 was profitable, but the studied FMOs were more profitable. The value/cost ratio of the studied FMOs varied from 2.4 to 5.5 in 2009 and from 2.6 to 4.7 in 2010 at Ndiaye. At

Fanaye, the value/cost ratio of the studied FMOs varied from 3.2 to 5.6 in 2009 and from 3.7 to 7.4 in 2010.

The FMOs supplying NPK and N during the HDS and WS, or conversely (FMO_2 and FMO_3) were also more profitable than FMO_1. FMO_2 and FMO_3 were particularly more profitable at Fanaye (4.8 to 4.9) than at Ndiaye (3.6 to 4.0), confirming the main hypothesis of the research. Instead of the seasonal applications of the recommended NPK fertilizer each season (FMO_1), one application of NPK fertilizer can be applied in only for one season (HDS or WS), accompanied by an application of N fertilizer in the other season (FMO_2 and FMO_3). Thereby, the cost of fertilization can be reduced with FMO_2 and FMO_3 from 26% compared to FMO_1.

The FMOs supplying NPK and NP during the HDS and WS, or conversely (FMO_4 and FMO_5) were also more profitable than FMO_1. FMO_4 and FMO_5 were particularly more profitable at Fanaye (3.8 to 3.9) than at Ndiaye (2.6 to 2.8), indicating that one application of NPK fertilizer can be used for only one season (HDS or WS), combined with the application of NP fertilizer in the other season (FMO_2 and FMO_3). Thus, K can be applied in one season per year leading to a reduction of the cost of fertilization by 7% compared to the recommended FMO_1.

The FMOs supplying NPK and NK during the HDS and WS, or conversely (FMO_6 and FMO_7) were also more profitable than FMO_1. FMO_6 and FMO_7 were also more profitable at Fanaye (3.6 to 4.0) than at Ndiaye (2.8 to 2.9), indicating that one application of NPK fertilizer can be used in only one season (HDS or WS), with the application of NK fertilizer in the other season (FMO_6 and FMO_7). As for potassium, P fertilizer can be applied in one season per year leading to a slight reduction of the cost of fertilization by 6% compared to the recommended FMO_1.

The FMOs supplying NP during the HDS and only N fertilizer during the WS, or conversely (FMO_8 and FMO_9) were the most profitable, giving the highest mean values of 4.9 to 5.1 and 6.2 to 6.3 at Ndiaye and Fanaye, respectively. FMO_8 and FMO_9 were the most profitable at the two sites during the two years. This is due to the significant reduction of the cost by the elimination of K application in the two seasons with only one application of P per year (HDS or WS). Instead of the seasonal applications of the recommended NPK fertilizer each season (FMO_1), one application of NP fertilizer can be used in only one season (HDS or WS), accompanied by the application of N fertilizer in the other season (FMO_8 and FMO_9). This would reduce the cost of fertilization by 47% compared to FMO_1.

The agronomic data and profitability analyses have confirmed that three FMOs can reduce the cost of fertilization and increase rice productivity.

The best option (NP-N: FMO_8 and FMO_9) was the most profitable. It reduced the cost of fertilizer by 47%. However, there is the risk that the long-term cultivation of rice without applying K fertilizer can lead to K deficiency. Hence, this option is not suitable for sustainable management of the intensive double cropping system of irrigated rice.

The second option (NPK-N FMO_2 and FMO_3) was also very profitable. It reduced the cost of fertilization by 26%. This option was consistent with previous results (Haefele *et al*., 2004; Bado *et al*., 2010) which indicated that the nutrients P and K can be applied in only one season per year (instead of two seasons) for sustaining soil nutrient status for sustainable management of soil fertility. The third option (NPK-NP: FMO_4 and FMO_5) was also beneficial but it was less profitable than the second one (NPK-N).

3.4. Soil P and K Variation and Sustainability of the Recommendation

Trends of soil extractable P and exchangeable K in the plots that received NPK fertilizers in HDS and only N fertilizer in WS (NPK-N) are showed in figure 4.

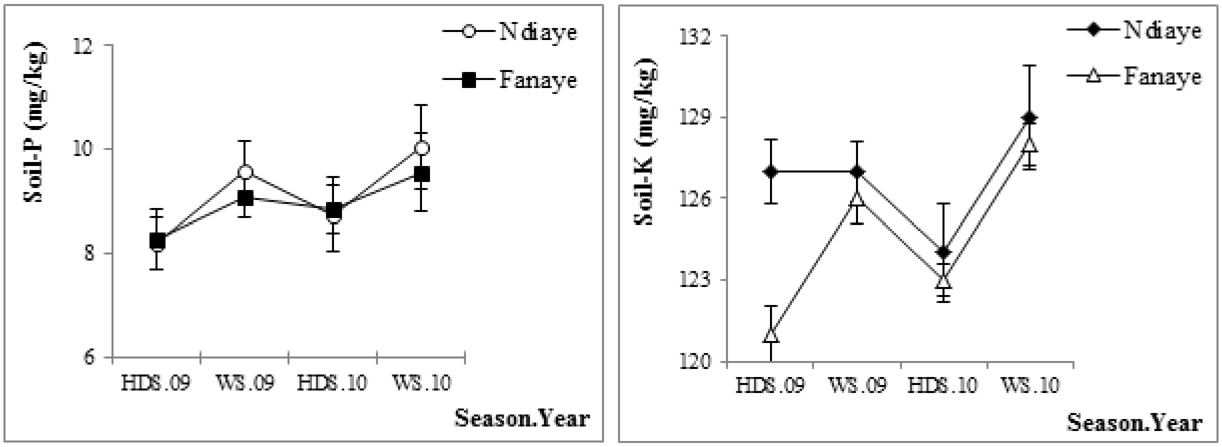

Figure 4. Trend of Soil-P and K level at Ndiaye and Fanaye during the four consecutive seasons during two years (2009-2010). NPK fertilizers are applied in Hot Dry Season (HDS) and only N fertilizer is applied in Wet Season (WS) every year.

At Ndiaye, soil extractable P varied from 8.18 mg kg^{-1} in Hot Dry Season 2009 (HDS.09) to 10 mg kg^{-1} in Wet Season 2010 (WS.10). Exchangeable K varied from 127 mg kg^{-1} in Hot Dry Season 2009 (HDS.09) to 129 mg kg^{-1} in Wet Season 2010 (WS.10).

At Fanaye, soil extractable P varied from 8.27 mg kg^{-1} in Hot Dry Season 2009 (HDS.09) to 9.55 mg kg^{-1} in Wet Season 2010 (WS.10). Exchangeable K varied from 121 mg kg^{-1} in Hot Dry Season 2009 (HDS.09) to 128 mg kg^{-1} in Wet Season 2010 (WS.10).

At both site, level of soil-P and K increased and decreased alternatively in WS and in HDS. That's probably due to the accumulation of P and K nutrients in wet season (WS.09 and WS.10) after application of NPK fertilizers the preceding season (HDS.09 and HDS.10). One application per year of 26 kg P ha^{-1} and 50 kg K ha^{-1} supplied by the recommended dose of NPK fertilizer seemed to provide enough P and K for two seasons.

Investigating the importance of soil extractable P on rice yield, Bado *et al*. (2007) determined a critical limit of 9 mg P kg^{-1} (Bray 1 P). P becomes a limiting factor for increasing rice yield when the soil supplies less than 9 mg P kg^{-1} and P fertilizer should be applied under such conditions in order to increase rice yields. Above this value, responses to P fertilizer applications are not expected (Bado *et al*., 2007). Data of soil extractable P should be used to confirm the necessity to apply P fertilizers to overcome this limiting factor. The recommended dose of NPK that supplies 26 kg P ha^{-1} seems to provide enough P to maintain soil extractable P around or beyond the critical limit. This can explain why one application of 26 kg P ha^{-1} per season can maintain good levels of soil extractable P and rice yields for two cropping seasons as we observed at the two sites. Based on our data, this is true when soil extractable P is very close to the critical limit of 9 mg P kg^{-1}.

Since 1991, AfricaRice has implemented a long-term fertility experiments (LTFE) in Senegal at the two sites. The main objective was to study the evolution of nutrient and soil fertility in an intensive irrigated rice system (Haefele *et al*., 2002). One of the interesting achievements is that NPK nutrient status and rice yields were maintained over 18 years (36 cropping seasons) with the seasonal applications of the recommended dose of NPK fertilizer supplying 120 kg N ha^{-1} , 26 kg P ha^{-1} and 50 kg K ha^{-1} (Bado *et al*., 2010). The LTFEs revealed that soil extractable P increased from 3.8 to 6.8 mg P kg^{-1} at Fanaye) and from 4.9 to 9.7 mg P ha^{-1} at Ndiaye with seasonal applications of the recommended dose of NPK fertilizer. Soil-P data from this research were on averagely very close to the critical limit (9 mg P kg^{-1}) for rice production (Bado *et al*., 2007) and were similar to those obtained in the LTFE with the seasonal application of 26 kg P ha^{-1} after 18 years of cultivation.

Our agronomic data confirmed that P could be applied in one season per year (instead of seasonal application) when soil extractable P reaches 7 to 9 mg P kg^{-1}. Otherwise, seasonal applications of P are necessary below these values of P to prevent any decline of soil extractable P. Using data from 16 cropping seasons, Haefele *et al*. (2004) simulated (linear regression) a possible decrease of soil extractable P of 0.08 mg P kg^{-1} per season with the application of the recommended 26 kg P ha^{-1} on the LTFE at Ndiaye when the extractable P of the original soil was 6.4 mg P-Bray1 kg^{-1}. This confirmed a depletion of soil P with the recommended dose of fertilizer when soil P was below the critical limit. However, the decrease in soil P over the 16 seasons did not cause any decline in yield. This could be clarified with more soil data from the LTFE.

The exchangeable K of the two sites was similar to those reported by Haefele *et al*. (2002) and Bado *et al*. (2010) on the LTFEs. There has been no significant depletion of soil K with the recommended doses of NPK fertilizers supplying 50 kg K ha^{-1} but rather increased at the two sites with the application of K fertilizers (Haefele *et al*., 2004; Bado *et al*., 2010). There was no depletion of soil K because of the high levels of soil K reserves generally observed in most of the irrigated lowland valleys in the Sahel and Sudan savannah (Buri *et al*., 1999; Wopereis *et al*., 1999; Haefele *et al*., 2004) and the seasonal applications of 50 kg K ha^{-1} provides enough K for sustainable management of this nutrient.

5. Conclusion

The main objective of this research was to investigate alternative management options to improve the productivity and profitability of the intensive double cropping system of irrigated rice. Three profitable management options were identified. It was concluded that when sol extractable phosphorous is higher than 7 mg P ha^{-1} (P-Bray1), the recommended NPK fertilizer can be applied in one season and only N fertilizer in the other season. This fertilizer management option reduces the cost of fertilization by 26% and maintains nutrient status for a sustainable management of soil fertility in the double rice cropping system.

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