Long-term effect of continuous cropping of irrigated rice on soil and yield trends in the Sahel of west Africa

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Abstract

The effects of 18 years continuous cropping of irrigated rice on soil and yields were studied in two long-term fertility experiments at Ndiaye and Fanaye in the Senegal River valley (west Africa). Rice was planted twice a year during the hot dry season (HDS) and wet season (WS) with different fertilizer treatments.

Soil organic carbon (SOC) under fallow varied from 7.1 g/kg at Fanaye to 11.0 g/kg at Ndiaye. Rice cropping maintained and increased SOC at Ndiaye and Fanaye, respectively, and fertilizer treatments did not affect SOC. Soil available P and exchangeable K were maintained or increased with long-term application of NPK fertilizers. Without any fertilizer, yields decreased by 60 kg/ha (1.5%) and 115 kg/ha (3%) per year at Fanaye and Ndiaye, respectively. Highest annual yield decreases were 268 kg/ha (3.6%) and 277 kg/ha (4.1%) at Fanaye and Ndiaye, respectively, when only N fertilizer was applied. Rice yields were only maintained with NPK fertilizers supplying at least 60 kg N, 26 kg P and 50 kg K/ha. It was concluded that the double cropping of irrigated rice does not decrease SOC and the application of the recommended doses of NPK fertilizer maintained rice yields for 18 years.

Introduction

Weak soil buffering capacity due to low soil organic carbon (SOC) and clay content, low cation exchange capacity (CEC) and P deficiency are the main limiting factors to agricultural productivity of the upland soils of west Africa. Data from many long-term experiments in upland soils show yield declines over time as a consequence of a decrease in SOC, soil acidification and a decrease of nutrient use efficiency (Bationo and Mokwunye, 1991; Bado *et al.*, 1997; Bationo, 2008). In contrast to the poor upland soils, lowland soils of the inland valleys have generally higher organic carbon and clay content, a better CEC and water-retention capacity, offering better conditions for crop production.

As in Asia, rice has become the most important cereal crop of the inland valleys of west Africa. Rice is cultivated as a staple food by farmers in the small inland valleys, or as a cash crop in many irrigated schemes. Consequently, the cropping systems are becoming more and more intensified and, whenever possible, many farmers grow two rice crops per year (during the wet and hot dry seasons). While the simulated potential yield of irrigated rice is 8–12 t/ha (Dingkuhn and Sow, 1997), the average yields in farmers' fields vary from 4 to 6 t/ha (Haefele *et al.*, 2002; Kebbeh and Miezan, 2003). This means that there is scope for increasing rice yields with the sustainable intensification of the existing cropping systems.

The long-term and intensive cultivation of rice with periodic flooding can affect the dynamics of SOC, soil pH, CEC and nutrient use efficiency (Cassman *et al.*, 1997). A key research question is whether long-term intensive lowland rice–rice cropping in the irrigated schemes is sustainable. Some results from long-term experiments in Asia showed yield declines of 70 to more than 200 kg/ha with best management practices over a period of 10–24 years (Flinn and De Datta, 1984; Cassman *et al.*, 1995, 1997). There is very little information on soil changes and rice crop yields in long-term intensive rice cultivation in Africa. Working with only 10 years data on two long-term fertility experiments (LTFEs) in west Africa, Haefele *et al.* (2002, 2004) found a slight but non-significant yield decline (–27 kg/ha per season) at one site and a significant yield increase (+86 kg/ha per season) at another site. A non-significant decrease in SOC was also observed. The authors recognized that because of the short duration of the experiments (10 years) and climatic influences, the observed yield trends could not give an accurate indication of the biophysical sustainability of the cropping system.

The overall objective of this study was to assess the sustainability of rice cropping in terms of soil fertility and yield stability using more data (18 years or 36 cropping seasons) from the same LTFEs. This research is mainly focused on soil P and K, SOC and yield trends under long-term intensive cropping of rice.

Materials and methods

Experimental sites

Two LTFEs were carried out over a period of 18 years (1991–2008) at the Africa Rice Center (AfricaRice) research farms in Ndiaye and Fanaye, both located in the Senegal River valley. Ndiaye (16°14′ N, 16°14′W) is located close to the coast (about 40 km inland) in the Senegal River delta. Soil salinity at the site and in the river delta is generally high, due to the occurrence of marine salt deposits in the sub-soil (Haefele *et al.*, 2002). The soil profile at Ndiaye corresponds to a typical Orthithionic Gleysol (FAO, 1998). The original soil contained at least 10 mg C/kg and 5 mg P/kg (Bray-1 P). Fanaye (16°33′ N, 15°46′ W) is located in the middle valley of the

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Senegal River, approximately 240 km inland, where natural soil salinity is low or absent. The soil profile in Fanaye belongs to a Eutric Vertisol (FAO, 1998). The original soil contained at least 6.5 mg C/kg and 4 mg P/kg (Bray-1 P). The climate of the two sites is characterized by a wet season (WS) from July to October with approximately 200 mm rainfall, a cold dry season from November to February and a hot dry season (HDS) from March to June (Dingkuhn and Sow, 1997; Haefele *et al.*, 2002).

Agronomic experiments

The LTFE was established at Ndiaye during the HDS of 1991. The first rice crop was cultivated to homogenize soil-fertility variability with the rice cultivar SIPI 692033, planted with a uniform application of N–P–K fertilizer supplying 120, 26 and 50 kg/ha. At Fanaye, soil-fertility variability was homogenized by growing different cultivars of rice during the cold dry season with the same uniform dose of NPK fertilizer used at Ndiaye. From 1991 to 1997, the medium-duration cultivar Jaya was used in the WS and short-duration IR 50 in the HDS. From the WS of 1997 (Ndiaye) and the HDS of 1998 (Fanaye), both cultivars were replaced by Sahel 108, a short-duration cultivar (Miézan and Diack, 1994).

Six fertilizer treatments with four replications were laid out in a randomized complete block design. Experimental plots measured 25 m^2 (5 × 5 m) and were separated by small (30 cm high) dikes. The six fertilizer treatments were: a control (without any fertilizer); the recommended dose of N fertilizer without P and K (120 kg N/ha, 0 kg P/ha, 0 kg K/ha); the recommended dose of NPK fertilizer (R_NPK: 120 kg N/ha, 26 kg P/ha and 50 kg K/ha); low dose of N, recommended P and K (L_NPK: 60 kg N/ha, 26 kg P/ha and 50 kg K/ha); high dose of N, recommended P and K (H_NPK: 180 kg N/ha, 26 kg P/ha and 50 kg K/ha); and recommended (medium) dose of N, high P and K (M_NPK: 120 kg N/ha, 52 kg P/ha and 100 kg K/ha). Urea (46% N), ammonium phosphate (18% N and 20% P) and potassium chloride (47% K) were used.

Rice seedlings were transplanted at the rate of 25 hills/m^2. Crop management was adjusted to the farmers' practice. For all fertilizer treatments, 50% N, 100% P and 100% K were broadcast at 21 days after transplanting. The remaining N dose was split-applied at panicle initiation (25%) and 10 days before flowering (25%). Herbicide (propanil, 6 L/ha) and manual weeding were used for weed control. Herbicide was applied once at 21 days after sowing, one day before the first N application; thereafter, plots were kept weed-free by manual weeding. Insecticide (carbofuran [Furadan]) was sometimes used at 25 kg/ha for insect-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 and the harvested straw was removed from the plots every season. Rice grain yields were determined from a 4 m^2 area in each plot at maturity and reported at a standard water content of 140 g water/kg fresh weight.

Soil sampling and analysis

Soil from each of the six fertilizer treatments was sampled at the end of DS 2007 (after 17 years of cultivation). Data of the original soils of the two sites are already published (Haefele *et al.*, 2002). However, in the absence of the original database with repeated values, it was not possible to conduct an analysis of variance in comparison with soil samples from the experimental plots. We selected some uncultivated areas (natural fallow) around the experiments to serve as a reference. These areas received the same water regimes (flooding and aeration) as the experimental plots. The sub-samples were mixed thoroughly to get a composite sample, air-dried immediately after collection and dried in the laboratory at 60°C for one week. The samples were analyzed in the AfricaRice soil laboratory. Soil organic C was determined using the wet digestion method (Walkley and Black, 1934). Available soil P was determined by the Bray-1 P method using the extractant 0.03 N NH_4F in 0.025 N HCl (Bray and Kurtz, 1945). Soil exchangeable K (K_{exch}) was extracted with 1 M NH4OACc solution (Helmke and Sparks, 1996).

Statistical data analysis

The statistical analyses of the rice yields were first done using the four factors: year, site, season and fertilizer treatments (Gomez and Gomez, 1983). SAS software was used for data calculations (SAS Institute, 1995). The relationships between rice yield variations and years of cultivation were tested with different models before selecting the simple linear model which best described the relationship between the two factors (equation 1):

$$Y\ (t/ha) = a\,X + b \qquad 1 \le X \le 18 \qquad [1]$$

Where Y = rice grain yield (dependent variable), X = number of years of cultivation (independent variable), *a* and *b* = the coefficient and the intercept of the linear regression, respectively (Gomez and Gomez, 1983).

Results and discussion

Soil organic carbon, phosphorous and potassium

The mean SOC of the uncultivated soil was higher ($P<0.01$) at Ndiaye (11.0 g/kg) than at Fanaye (7.1 g/kg) (Table 1). Data of the original soil also indicated that the site of Ndiaye contained more carbon (10.0 g/kg) than Fanaye (6.6 g/kg) (Haefele *et al.*, 2004). At Ndiaye, SOC varied from 10.5 g/kg in the M_NPK treatment to 12.3 g/kg in the H_NPK treatment, with no significant differences between the fertilizer treatments. At Fanaye, SOC ranged from 12.9 g/kg in the control plots to 13.6 g/kg in the R_NPK plots. SOC was not decreased by long-term cultivation at either site, but was increased at Fanaye.

Table 1. Effects of 18 years of continuous lowland irrigated rice monocropping with NPK chemical fertilizer application on soil organic carbon and extractable Bray-1 P (0–20 cm surface layer), at two experimental sites (Ndiaye and Fanaye).

Site	Treatment: N-P-K fertilizer (kg/ha)	Organic carbon (SOC, g/kg)	Extractable P (Bray-1, mg/kg)	Exchangeable K (cmol/kg)
Ndiaye	Control (0N–0P–0K)	10.6	5.3 ^{c}	0.56
	L_NPK: 60N–26P–50K	11.4	9.9 ^{b}	0.59
	120N–0P–0K	11.7	4.2 ^{c}	0.64
	R_NPK: 120N–26P–50K	11.0	9.7 ^{b}	0.53
	M_NPK: 120N–52P–100K	10.5	19.7 ^{a}	0.66
	H_NPK: 180N–26P–50K	12.3	8.9 ^{b}	0.49
	Uncultivated soil	11.0	4.9 ^{c}	0.61
Fanaye	Control (0N–0P–0K)	12.9 ^{a}	4.2 ^{b}	0.58 ^{a}
	L_NPK: 60N–26P–50K	13.3 ^{a}	6.2 ^{a}	0.55 ^{ab}
	120N–0P–0K	13.5 ^{a}	2.8 ^{c}	0.45 ^{c}
	R_NPK: 120N–26P–50K	13.6 ^{a}	6.8 a	0.48 ^{bc}
	M_NPK: 120N–52P–100K	13.2 ^{a}	7.1 ^{a}	0.63 ^{a}
	H_NPK: 180N–26P–50K	13.3 ^{a}	5.2 ^{b}	0.45 ^{c}
	Uncultivated soil	7.1 ^{b}	3.8 ^{c}	0.57 ^{ab}

Values in columns followed by the same letters for the same site are not significantly different ($P>0.05$) according the Fisher test. Significant differences were not observed for soil organic carbon at Ndiaye.

Soil-extractable Bray-1 P of the uncultivated soil was very low (3.8 mg/kg at Fanaye and 4.9 mg/kg at Ndiaye). All NPK fertilizer treatments increased soil-extractable P at the two sites (Table 1). The soil-available P ranged from 4.2 mg/kg (N only) to 19.7 mg/kg (M_NPK) at Ndiaye, and from 2.8 (N only) to 7.1 mg/kg (M_NPK) at Fanaye.

While soil exchangeable K (K_{exch}) was affected by fertilizer application at Fanaye, it was not at Ndiaye. In general, K_{exch} was increased at the two sites with the application of K fertilizers. The lowest levels of K_{exch} were noted with the high doses of N fertilizers (180 kg N/ha) at both sites (Table 1).

Yield variations and trends

Grain yields were highly affected by fertilizer application ($P<0.001$), year ($P<0.001$) and site ($P<0.0001$). However, grain yields were not affected by the season (Table 2). All interactions — simple (site–season; site–year; site–fertilizer; year–site; season–site and year–fertilizer), triple (site–year–season; site–season–fertilizer; year–season–fertilizer and site–year–fertilizer) and quadruple (site–year–season–fertilizer) — were significant for grain yield.

The parameters of the linear regression models used to analyze grain yield trends over the 18 years are presented (Table 3). The intercepts of the linear regression indicate the mean grain yields during the first year of cultivation. Considering the yield trends (Table 3, Fig. 1 and 2), two main groups of fertilizer treatments were identified: (i) the control treatment and the recommended N dose alone without P and K, and (ii) the NPK treatments.

Long-term cultivation without fertilizer application decreased grain yields by 115 kg/ha per year, with a confidence interval of 59–173 kg/ha ($P<0.05$) at Ndiaye during the WS (Table 3). The same practice induced an annual yield loss of 60 kg/ha at Fanaye during the same WS. Thus, long-term cultivation without fertilizer decreased rice yields by 1.5% per year at Fanaye and 3% at Ndiaye during the WS. While a high yield of 7 t/ha was obtained in the first year of cultivation, N-fertilizer application alone induced the highest annual yield decreases at both sites, except for Fanaye HDS (Table 1, Fig. 1 and 2). The rice yield decreased by 268 kg/ha (–3.6%) at Fanaye and 277 kg/ha (–4.1%) at Ndiaye during the WS. A significant yield decrease of 147 kg/ha was observed during the HDS at Ndiaye (Table 3). With the NPK treatments, there was no significant linear relationship (*P*>0.05) between yield variations and years, and no significant yield decline was observed at the two sites when NPK fertilizers were applied (Table 3; Fig. 1 and 2). However, slight (non-significant) yield decreases (*P*>0.05) were always observed during the WS at both sites, while NPK fertilizers seemed to increase rice yields (*P*>0.05) during the HDS (Table 3).

Table 2. Influence of year, site, season and fertilizer on rice grain yields at Ndiaye and Fanaye between 1991 and 2008

Source of variations	**Degrees of freedom**	**F value**	**Probability level**
Site	1	41.84	<0.001
Year	17	38.95	<0.001
Season	1	0.02	0.8939
Fertilizer	5	1002.47	<0.001
Site × season	1	207.32	<0.001
Site × year	17	23.55	<0.001
Site × fertilizer	5	10.19	<0.001
Season × fertilizer	5	20.30	<0.001
Year × fertilizer	85	4.55	<0.001
Site × year × season	13	18.81	<0.001
Site × season × fertilizer	5	3.47	<0.005
Year × season × fertilizer	75	3.13	<0.001
Site × year × fertilizer	85	3.41	<0.001
Site × year × season × fertilizer	65	2.57	<0.001

Discussion

In comparison with the uncultivated soil, SOC was maintained at the same level at Ndiaye and even increased at Fanaye with rice cropping. Working on the same two LTFEs, Haefele *et al.* (2004) report a higher SOC in cultivated soils at one site (Fanaye), while a slight but non-significant decreasing trend of SOC at the other site (Ndiaye). Probably because of the limited amount of data (three sample dates) and spatial variability, the authors recognized that they could not conclude that SOC did not change. Unfortunately, soil samples were not taken every year in the LTFE and there are insufficient data to assess the trends of SOC over years. Our data also confirm higher SOC in the cultivated soil at Fanaye and treatments with NPK fertilizer applications always had higher SOC. Consequently, we can at least conclude that SOC did not decrease with rice cropping at either site, but was rather increased at one site (Fanaye).

The recycling of crop residues and roots in the flooded conditions of irrigated rice systems can explain the status of SOC. The decomposition of plant residues is typically slower in submerged than in aerated soil (Powlson and Olk, 2000; Regmi *et al.*, 2002; Sahrawat, 2004; Zhang and He, 2004; Mirasol *et al.*, 2008). Crop residues are continuously recycled in the soil twice a year as a source of carbon, which are incorporated into the young soil organic matter fraction (Cassman *et al.*, 1995; Olk *et al.*, 1996, 2000; Bronson *et al.*, 1998; Witt *et al.*, 2000). A significant increase of SOC was observed at Fanaye, probably because of the low initial level of SOC. After 17 years of cultivation, there was no significant difference in SOC between the cultivated soils at the two sites. The SOC had increased in the low-C content soil at Fanaye to the same level as at Ndiaye. The buildup of SOC by periodic anaerobic conditions seemed to raise SOC to an equilibrium of 11–13 mg C/kg. More significant increases of SOC will probably not occur during the coming years.

Low yields and significant decreases in yields over the years in the control treatment and N fertilizer without PK plots may be explained by the initial poor soil-fertility status. The low levels of extractable P in the original soil confirmed the need for P-fertilizer applications to overtake the critical limit of soil P for rice (Bado *et al.*, 2008). The high yields obtained with N-fertilizer alone without PK treatment during the first 3 years, followed by the quick yield decline, showed the limiting effect of these nutrients with time of cultivation.

In general, most of the irrigated lowland valleys in the Sahel and Sudan savannah have considerable soil K reserves (Buri *et al.*, 1999; Wopereis *et al.*, 1999; Haefele *et al.,* 2004). Probably because of the relatively high soil K status, the exchangeable K of the LTFE did not show any significant depletion with the recommended doses of NPK fertilizer as already noted by Haefele *et al.* (2004). However, the highest doses of N fertilizers (≥180 kg N/ha) can probably induce K depletion with long-term cropping.

The maintenance or buildup of SOC in flooded conditions, coupled with the improvement of soil chemical properties (Sahrawat, 2004) and better use of nutrients both from soil and fertilizers, can explain the yield trends during the 18 years of cropping. Except for the control treatment (without any fertilizer) and the treatment

Table 3. Rice grain yields in the first year of cultivation, annual variations in yield and correlation coefficient of the linear equations between years of cultivation for each season (hot dry and wet) and rice grain yields during 18 years (1991–2008) in the delta (Ndiaye) and middle (Fanaye) valley of the Senegal River

Site	**Season**	**NPK fertilizer (kg/ha nutrients)**	**Intercept t/ha (*b*)**	**Yield trends kg/ha (*a*)**	**Yield variations % per year**	**Coefficient of determination (R^2)**	**No. values (*n*)**
Ndiaye	Hot dry season	Control (0–0–0)	3.3	–49	–1.5	0.15	13
		120–0–0	6.1	–147 (–258; –37)†	–2.8	0.37*	16
		60–26–50	5.1	92	1.8	0.15	17
		120–26–50	6.9	19	0.3	0.01	17
		120–52–100	6.6	32	0.5	0.01	17
		180–26–50	7.3	13	0.2	0.03	17
	Wet season	Control (0–0–0)	3.9	–115 (–173; –59)	–2.9	0.58**	16
		120–0–0	6.8	–277 (–362; –188)	–4.1	0.77***	16
		60–26–50	6.1	–59	–0.1	0.14	16
		120–26–50	7.3	–78	–1.1	0.20	16
		120–52–100	7.3	–100	–1.4	0.20	16
		180–26–50	7.1	–54	–0.8	0.08	16
Fanaye	Hot dry season	Control (0–0–0)	2.2	–47	–2.1	0.14	16
		120–0–0	4.7	–46	–0.9	0.06	16
		60–26–50	4.9	–44	–0.9	0.05	16
		120–26–50	6.1	24	0.4	0.01	15
		120–52–100	6.0	60	1.0	0.06	16
		180–26–50	6.8	70	1.0	0.08	16
	Wet season	Control (0–0–0)	4.0	–60 (–124; 3)	–1.5	0.22*	17
		120–0–0	7.4	–268 (–372; –166)	–3.6	0.67***	17
		60–26–50	5.9	–23	–0.4	0.02	17
		120–26–50	7.3	–68	–0.9	0.10	17
		120–52–100	7.3	–42	–0.6	0.07	17
		180–26–50	7.9	–62	–0.8	0.06	17

*, **, ***, significant at 0.05, 0.01 and 0.001 probability levels, respectively, according the Fisher test. † Confidence interval of yield variations at 95% probability level. Each *n* value represents the mean yield of 4 values of the 4 replications.

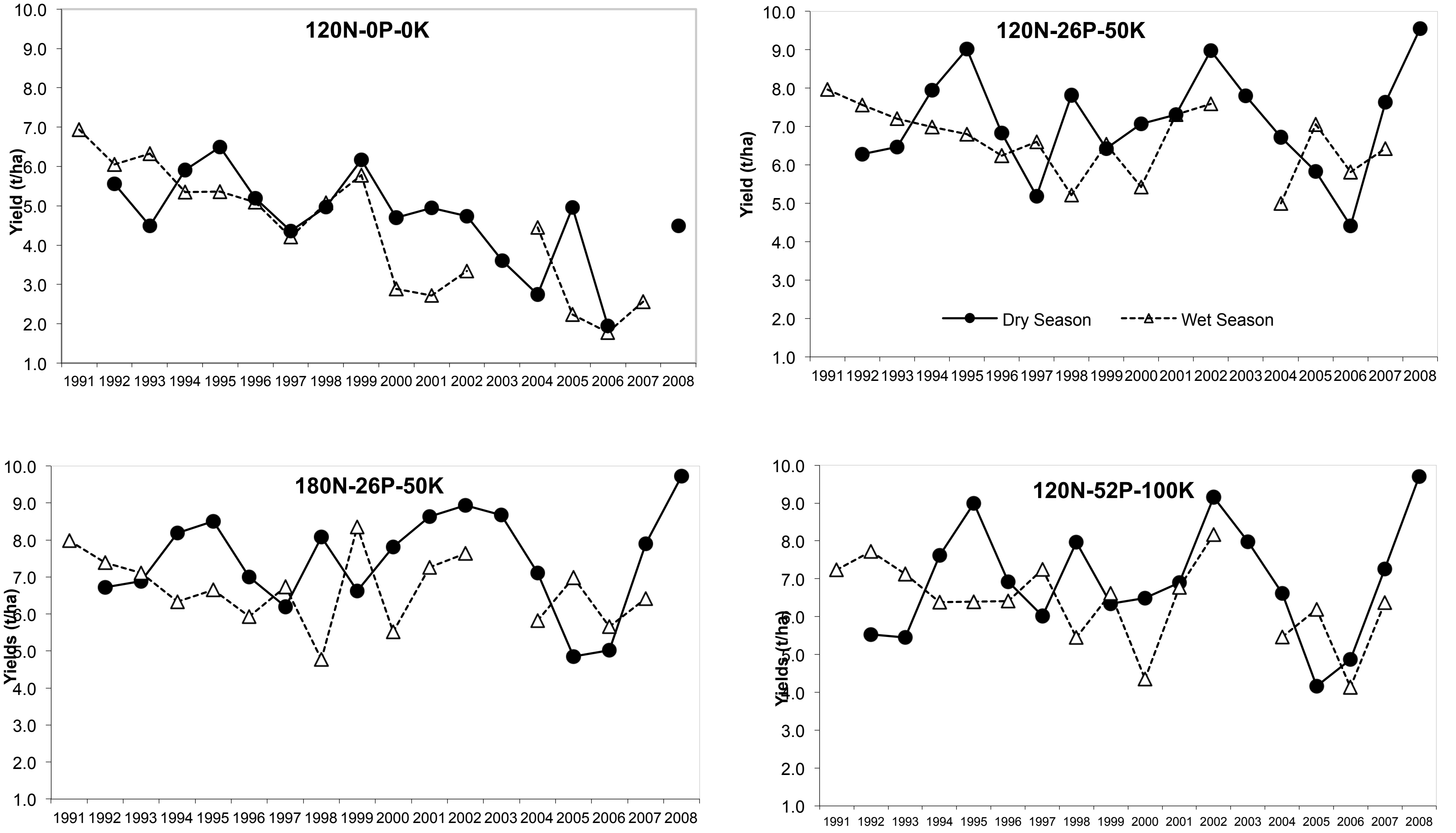

Figure 1: Influence of fertilizer application on rice grain yields during the hot dry season (HDS) and wet season (WS) at Ndiaye in the delta valley of the Senegal River over 18 years (1991–2008).

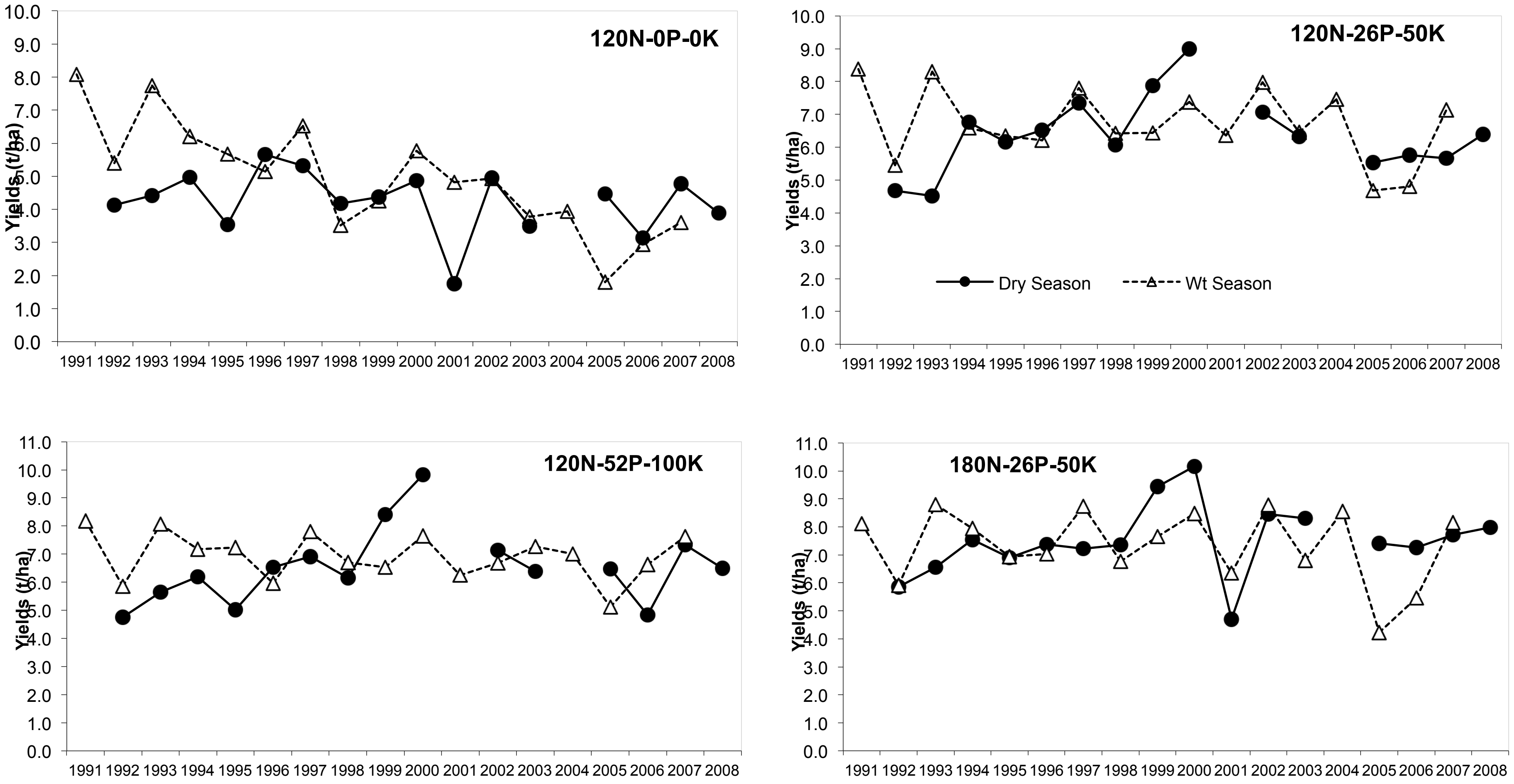

Figure 2: Influence of fertilizer application on rice grain yields during the hot dry season (HDS) and wet season (WS) at Fanaye in the middle valley of the Senegal River over 18 years (1991–2008).

without P or K fertilizer, rice grain yields were maintained during the 18 years with the seasonal applications of chemical NPK fertilizers. Using the yields of the best NPK treatment, Haefele *et al.* (2002) observed a slight but non-significant yield decline (–27 kg/ha per season) at Ndiaye and significant yield increase at Fanaye (+86 kg/ha per season). Otherwise, no yield declines were observed when the three NPK nutrients were applied. The authors recognized that because of the short duration of the experiments (10 years) and extreme conditions of the Sahelian climate, the observed yield trends could not give an accurate indication of the biophysical sustainability of the cropping system. They probably did not observe the interactions within the factors site, season and fertilizer as we did with 36 cropping seasons (Table 2). The climatic variability and site-specific crop management at the two sites may explain the influence of sites and season on grain yield (Dingkuhn and Sow, 1997). The hot dry season was found to be most productive in the coastal zone of the delta (Ndiaye) because of the moderate air temperatures in proximity to the sea. Cold-induced spikelet sterility that frequently affects rice yield (Dingkhun and Sow, 1997), climatic variations and harvest operation may explain the diverse effects of site and season on biomass and grain yields.

The data confirmed that rice yields were maintained over 18 years (36 seasons) of continuous cropping, probably because of the improvement of soil chemical fertility with flooding (Sahrawat, 1998) and the maintenance of SOC and NPK nutrient status with the seasonal applications of NPK fertilizers. This is confirmed for all the three treatments of NPK fertilizer and not only for the best treatment per season as observed by Haefele *et al.* (2002).

Conclusions

Soil organic carbon was maintained or increased irrespective of fertilizer application and rice yields — it declined only when rice was cultivated without NPK fertilizer or when N-fertilizer alone was used. However, these data suggest research to develop alternative and better management options of chemical fertilizers to improve irrigated rice productivity and profitability. While N should be applied each season, it is probably not necessary to apply P and K each season. For example, seasonal applications of N (each cropping season) and annual applications (one season per year) of P and K could be an option to improve fertilizer management, rice production and profitability.

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