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Long-term fertility experiments for irrigated rice in the West African Sahel: effect on soil characteristics

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Abstract

Long-term fertility experiments (LTFEs) are a tool to investigate the sustainability of cropping systems. The present study analyzed two LTFEs for intensive rice-based irrigated systems in the Senegal River valley at Ndiaye and Fanaye (Sahel savanna). The trials were established in 1991, contain six different fertilizer treatments and rice is grown two times per year. Soil types are a typical Orthithionic Gleysol and an Eutric Vertisol at Ndiaye and Fanaye, respectively. The objectives of the presented study were to analyze the effect of intensive irrigated rice cropping on the soil resource base by studying the changes of soil characteristics over time and by comparing soil N, P and K pools in different fertilizer treatments. In the LTFE at Ndiaye, topsoil pH values increased significantly from 5.5 to about 6.5 and electrical conductivity was high but remained stable. Soil organic carbon (SOC) and total soil nitrogen (TSN) dropped slightly after 16 consecutive seasons but the difference was statistically not significant. At both sites, exchangeable N ranged between 1.6 and 2.8% of TSN and fixed N accounted for 5.5–8.2% of TSN, with slightly higher values in Fanaye. Treatment differences in N dose had no significant effect on these parameters. Results of $\delta^{13}C$ analysis showed a decrease due to rice cropping at both sites, and the measurements indicate high turnover rates of soil organic matter. Soil analyses of total soil P and K and of different pools indicated only small changes when these elements were applied at medium quantities. In contrast, treatments with N application only showed considerable soil P and K depletion, and rice cultivation without P and/or K application cannot maintain soil fertility. The soil mining process is relatively quick for P due to the naturally low soil P status, whereas the high soil K reserves buffer even important negative K balances for decades. It is concluded that irrigated rice cultivation in the region can maintain soil fertility if at least medium P doses are applied together with nitrogen.

Keywords: $\delta^{13}C$ analysis; Irrigated rice; Long-term fertility experiment; Soil nutrient pool analysis; West Africa

1. Introduction

In 1991, the West Africa Rice Development Association (WARDA) established long-term fertility experiments (LTFE) at its research farms Ndiaye and Fanaye in the Senegal River valley. Intention was to monitor and quantify long-term changes in soil fertility and rice yield response to N, P and K fertilizer input. A detailed trial description and agronomic results of 20 consecutive seasons were given by Haefele et al. (2002). Best treatments at both sites and in both seasons yielded on average between 6.7 and 7.6 Mg ha^{-1} per crop. Highest yields indicated a

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not significant yield decline of −27 kg per season in Ndiaye and a significant increase in Fanaye (+86 kg per season). Using crop simulation tools and actual weather data from both sites, it was concluded that observed yield trends could largely be explained by climatic influences. Nevertheless, this does not exclude a soil quality decline. Changes of soil characteristics may not influence crop productivity as long as they do not reach critical levels, a phenomenon well known, e.g. for soil alkalinity. Similarly, any change in nutrient availability remains without impact on yield as long as plant uptake needed to reach these yields stays below potentially plant available nutrients. Therefore, this study of WARDA's LTFE trials in the Senegal River valley presents an analysis of soil characteristics. In particular, trial and treatment induced influences on soil organic matter, soil N, soil P and soil K pools were analyzed in detail.

Soil organic matter has an important influence on a range of physical and chemical soil characteristics and contributes significant amounts of plant nutrients important for crop production, and the evolution of SOM resulting from crop cultivation is an important indicator for the sustainability evaluation of the respective cropping system. Neue et al. (1994) stated, that wetland rice agriculture is probably the only agricultural system that has conserved or even increased soil organic matter. This increase was mainly attributed to higher net primary production in tropical wetland soils rather than retarded decomposition (Neue and Scharpenseel, 1987; Neue, 1991), but both processes and the equilibrium reached are site-specific and depend on parameters like nutrient supply, pH, temperature, and texture (e.g. Neue et al., 1994; Zech et al., 1997).

Soil organic matter is an important soil N pool, but relations between SOM and rice plant N uptake or yield are often scattered and depend on a large number of environmental factors. Yield declines in LTFEs at the International Rice Research Institute attributed to a reduction of indigenous soil N supply, were accompanied by an increase of SOM (De Datta et al., 1988; Cassman et al., 1995a). Other important soil N pools are exchangeable and non-exchangeable ammonium and both pools were repeatedly used as indicators for soil N supply, to study transformation of applied N fertilizer or to characterize plant N uptake (e.g. Schneiders, 1998).

Similarly, analysis of soil P and K pools were used to investigate the influence of cropping and cropping practices on the soil resource base. Soil P fractions have been used to study transformation of applied P fertilizer (Zhang and MacKenzie, 1997), to investigate the impact of long-term cropping on soil P (Hedley et al., 1982b; Schwab and Kulyingyong, 1989), to interpret P soil test values, and to characterize the development of soil P pools in relation to soil type and soil evolution (Cross and Schlesinger, 1995; Smeck, 1985).

Potassium has received much less attention in rice research than nitrogen, despite the fact that total K uptake can be higher than N uptake and that K has an important function in many physiological processes. Negative K balances in intensive irrigated rice systems and yield limitation caused by insufficient K supply were reported from several Asian countries (e.g. De Datta and Mikkelsen, 1985; Dobermann et al., 1996a,b). Soil K pool analysis was used to determine the contribution of different soil K pools and soil depths to crop growth, to determine the fate of K fertilizer in different soil types, or to investigate the capacity of specific plant species to extract K from different K pools (e.g. Barber and Matthews, 1962; Sharpley, 1990; Richards and Bates, 1988).

The objective of the presented study was to analyze the effect of intensive irrigated rice cropping on the soil resource base by studying the development of soil characteristics in the LTFE trials over time and by comparing soil nutrient pools in different fertilizer treatments.

2. Materials and methods

2.1. Trial description

The LTFE was established at WARDA's two research farms in Ndiaye and Fanaye (Senegal) in the wet season (WS) 1991. Ndiaye (16°14′N, 16°14′W) is situated close to the coast (about 40 km inland) in the delta of the Senegal River, Fanaye (16°33′N, 15°46′W) is located in the middle valley of the Senegal River approximately 240 km inland. Soil type in Ndiaye is a typical Orthithionic Gleysol and in Fanaye a Eutric Vertisol according to the FAO systematic (FAO, 1998). Soil characteristics from profiles adjacent to the trials

Table 1
Soil characteristics for representative soil profiles at WARDA's research farms in Ndiaye and Fanaye[a]

Horizon	Depth (cm)	D_b[b] (g cm^{-3})	pH[c]	CEC (cmol kg^{-1})	C_{org} (%)	N (%)	Sand[d] (% soil < 2 mm)	Silt[d] (% soil < 2 mm)	Clay[d] (% soil < 2 mm)
Ndiaye									
Ap	0–21	1.50	6.5	13.0	0.93	0.10	16	44	40
Bg	21–53	1.59	4.6	19.1	0.43	0.03	16	30	54
Bsyg	53–73	1.38	3.9	25.5	0.32	0.01	10	21	69
2Cjr	73–100	1.58	4.2	9.0	0.20	0.01	54	11	35
Fanaye									
Ap	0–10	1.37	6.8	26.2	0.75	0.08	8	28	64
Bw1	10–51	1.41	6.7	27.1	0.42	0.04	8	25	67
Bw2	51–100	1.48	5.7	25.8	0.38	0.04	8	24	68

[a] The soil in Ndiaye was classified as an Orthithionic Gleysol and soil type in Fanaye was a Eutric Vertisol (FAO, 1998).

[b] Bulk density.

[c] pH_{H_2O} in the 1:2.5 extract.

[d] Sand: 2000−63 μm, silt: 63−2 μm, clay < 2 μm.

are given in Table 1. Dominant clay minerals in the qualitative clay analysis at both sites were kaolinite and smectite (montmorillonite).

At both sites, a randomized complete block design with four replications and six different treatments was installed. Each plot has a size of 5 m × 5 m. Fertilizer treatments were applied to the same plots each season in a continuous rice double-cropping system and all straw was removed (Table 2). Treatment 0 (T0) is the control without any fertilizer application and T1 represents the than existing fertilizer recommendation (120 kg N ha^{-1}, 26 kg P ha^{-1} and 50 kg K ha^{-1}). Treatment 4 and 5 vary the N-dose to 180 and 60 kg N ha^{-1}, respectively. T2 has a high dose of P and K (52 P and 100 kg K ha^{-1}) whereas in T3 no P or K is applied. For N, P, and K treatments in Ndiaye, 50% N, 100% P and 100% K of the fertilizer dose were broadcast on the 23rd day after transplanting. The remaining N dose was applied in equal splits at panicle initiation and 10 days before flowering. At Fanaye, P and K were applied basal before leveling according to the treatment. N-application rate and timing were as in Ndiaye. Applied fertilizers were urea, triple-super phosphate and potassium chloride. For further details refer to Haefele et al. (2002).

2.2. Soil sampling and soil analysis

In order to determine the effect of continuous rice cropping and different fertilizer treatments on the soil, three different sets of soil samples were analyzed. The first set included topsoil samples (0–0.2 m) taken at the onset of each season in each subplot of the trial. Four sub-samples were taken with an auger in each corner of the subplot, 0.5 m away from the bunds. The four sub-samples were thoroughly mixed, air dried,

Table 2
Fertilizer treatments in the analyzed LTFEs in Senegal

Site	Cropping intensity	Treatment	Fertilizer dose		
			N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
Ndiaye (Senegal River delta) and Fanaye (Senegal River middle valley)	Two rice crops per year since 1991	T0	0	0	0
		T1	120	26	50
		T2	120	52	100
		T3	120	0	0
		T4	180	26	50
		T5	60	26	50

grounded and stored. Unfortunately most samples of Fanaye and some samples from Ndiaye were lost. Methods used for analyses of the remaining samples were pH_{H_2O} of the 1:2.5 extract, electrical conductivity of the 1:5 extract ($EC_{1:5}$), Bray1-P (Bray and Kurtz, 1945), exchangeable bases and cation exchange capacity (cation extraction with 0.2 M NH_4Cl and subsequent displacement of exchangeable NH_4-ions with 0.2 M KNO_3; modified from Sumner and Miller, 1996), organic C and total N (CHN-analyzer calibrated with acetanilide; inorganic C analysis was negative at both sites).

A second sample set was taken at both sites at the onset of the 1998 WS, where all treatments and replications were sampled in three depth steps (0–0.2, 0.2–0.5 and 0.5–0.7 m). In each subplot these samples were taken at two points (1.5 m from the center), and samples of the same depth were mixed after air drying. By comparing different soil nutrient pools for N, P and K in plots with different mineral fertilizer treatments, the effect of the latter on soil nutrient fractions was studied. Organic C and total N were determined by combustion with the CHN-analyzer. Exchangeable NH_4 was analyzed according to Keeney and Nelson (1982) and fixed NH_4 according to Silva and Bremner (1966). Seven soil P fractions were extracted according to Hedley et al. (1982a, 1994). The original fractionation scheme was shortened by excluding the ultra-sound treatment. Fractions analyzed were therefore the P_{resin} fraction, organic and inorganic fractions extracted with $NaHCO_3$, organic and inorganic fractions extracted with NaOH, the HCl fraction, and the residual fraction extracted with concentrated H_2SO_4. Phosphorus in the extracts was determined with the colorimetric ascorbic acid method according to Kuo (1996).

K pools analyzed were exchangeable K (K_{exch}) and non-exchangeable K. K_{exch} was extracted with 1 M NH_4OAc solution (Helmke and Sparks, 1996). For determination of non-exchangeable K, a sub-sample was first treated with cold 0.1 M HNO_3. Non-exchangeable K was afterwards extracted repeatedly (7×) with boiling 1 M HNO_3 solution according to Richards and Bates (1988). By subtracting K_{exch} from the total amount of K in all eight extractions, the total amount of extracted non-exchangeable K was calculated (“Mactotal” according to the same authors). The constant amount of K released in the last three HNO_3 extractions was called constant rate K (CRK) according to Haylock (1956). The cumulative difference between CRK and Mactotal was called “StepK” (Richards and Bates, 1988). Potassium in extraction solutions was always determined by Atomic Emission Spectroscopy.

For total elemental analysis of P and K, X-ray fluorescence spectroscopy (wavelength dispersive spectrometer, Philips) of fine-ground sub-samples was used. For the analysis, fused discs were prepared with $Li_2Bo_4O_7$. Procedures followed descriptions given by Karathanasis and Hajek (1996).

A third set of samples served to analyze the effect of irrigated rice cropping on soil organic matter. At each site, one soil profile was sampled in 0.1 m steps in the LTFE (T3, replication 3), and at an adjacent site with natural vegetation and no obvious cropping history (at both farms within 400 m from the LTFE). These samples were analyzed for soil organic carbon (SOC) and total soil nitrogen (TSN) as described above. Fine ground plant samples (from the dominant species at the profile site) and soil samples were analyzed for their ^{13}C to ^{12}C isotope ratio using a mass spectrometer (Isotope Ratio Mass Spectrometer Delta Plus, Thermo Quest/Finnigan). Calcite destruction prior to analysis was not necessary for any sample. Isotope ratios of ^{13}C to ^{12}C are expressed as $\delta^{13}C$ values, which refer to the PDB-standard (international calcite standard from the geological Pee-Dee formation of *Belemnitella americana* in South Carolina). The $\delta^{13}C$ values were calculated as follows:

$$\delta^{13}C \frac{(^{13}C/^{12}C)\text{sample} - (^{13}C/^{12}C)\text{PDB standard}}{(^{13}C/^{12}C)\text{PDB standard}} \times 1000‰$$

CO_2 gas calibrated against the PDB-standard served as reference during measurements (standard deviation of 0.05‰).

All analysis was conducted at the WARDA research station in St. Louis, Senegal and at the Soil Science Department of Hamburg University, Germany.

2.3. Statistical analyses

Statistical analysis was conducted according to Gomez and Gomez (1984) using STATISTICA software. The level of significance in the analysis of variance was always set to a P-level of 0.05. For comparison of treatment means, we used the Duncan's multiple range test with $\alpha < 0.05$.

3. Results

Trends of pH and EC in the topsoil (0.0–0.2 m) since initiation of the experiments are shown in Fig. 1. Presented are average values of all treatments, because statistical analysis did not reveal any significant difference between treatments. In Ndiaye, a continuous rise of pH from 5.5 in 1991 to about 6.5 in the HDS 2000 was observed and linear regression is highly significant. In Fanaye, average pH values were higher but due to missing samples no trend analysis was possible. Saline conditions during soil formation caused higher soil salinity in Ndiaye compared to Fanaye. In Ndiaye average $EC_{1:5}$ was always below 0.5 mS cm^{-1} with the exception of both seasons in 1999. If this year was excluded from the analysis, no trend over time significantly different from zero could

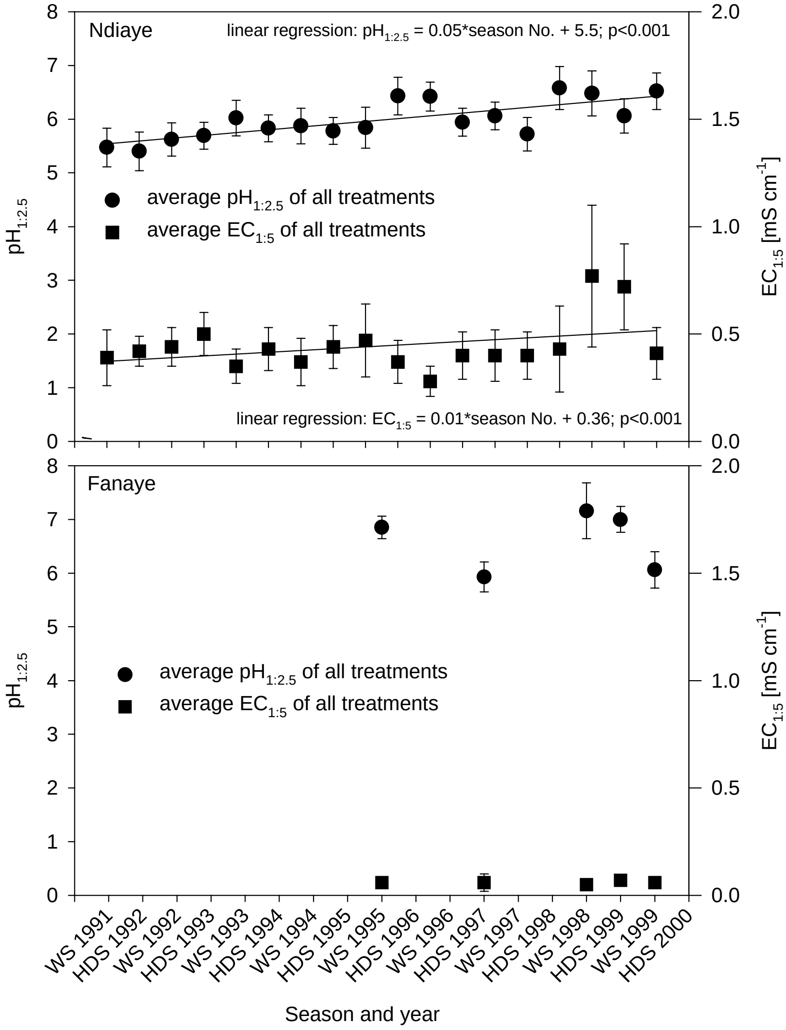

Fig. 1. Development of soil reaction ($pH_{1:2.5}$) and electrical conductivity ($EC_{1:5}$) in the topsoil (0.0–0.2 m) for the LTFE sites Ndiaye and Fanaye in the Senegal river region. The trials were established in 1991. Soils samples were taken at the onset of the WS and the hot dry season (HDS). Bars indicate standard deviation.

be detected. Average $EC_{1:5}$ in Fanaye was constant and always below 0.1 mS cm^{-1}.

Soil samples of all treatments from the WS 1991, WS 1997 and WS 1999 in Ndiaye were analyzed for SOC, TSN and C/N ratio. In the WS 1991, average SOC concentration was 0.94%, TSN concentration was 0.090% and the C/N ratio was 10.5. In the WS 1997 average values determined were 0.89% SOC, 0.088% TSN, and 10.2 was the C/N ratio. In the WS 1999, average values determined were 0.82% SOC, 0.080% TSN, and the C/N was 10.3. Although this indicates a decreasing trend of SOC and TSN, the differences between all three sampling dates were statistically not significant.

For the WS 1999, the same parameters were analyzed for both sites and different soil horizons (Table 3). Clear differences of SOC and TSN were found between sites and depths, but mineral fertilizer treatments had no significant impact on these parameters at any site. Comparison of SOC and TSN content in cultivated and uncultivated (“natural”) soils at Ndiaye and Fanaye is presented in Fig. 2a and b, respectively. At both sites, differences between cultivated and uncultivated soils were restricted to the topsoil and SOC and TSN content below 0.2 m depth was almost identical. In Ndiaye, both characteristics were lower in the cultivated soil, whereas at Fanaye topsoil values for SOC and TSN were lower in the uncultivated profile. Differences between shown TSN concentrations in Table 3 and Fig. 2 are due to the presentation of average values for all treatments and four replications in Table 3 and results from one soil profile in a T3 subplot (replication 3) in Fig. 2.

Results of $\delta^{13}C$ analysis showed a decrease due to cultivation at both sites (Fig. 2), which was most pronounced in the topsoil. Whilst $\delta^{13}C$ values of uncultivated soils ranged between −18 to −20‰, topsoil values of cultivated soils were <−24‰. Cultivation induced lower $\delta^{13}C$ values were limited to the uppermost 0.5 m in Fanaye, whereas they went down to 0.8 m in Ndiaye. Additionally, the cultivated soil at Ndiaye showed a maximum from 0.3 to 0.5 m depth. Plant samples analyzed resulted in average values of −26.7‰ for *Oryza sativa* L. (roots, culm, leaves and panicles), of −14.9‰ for *Diplachne fusca* (L.) P. Beauv. ex Stapf (roots, straw), of −26.7‰ for *Bolboschoenus maritimus* (L.) Palla (roots, straw), and of −27.4‰ for *Acacia raddiana* Savi. (roots, twigs, leaves, seeds). *D. fusca* and *B. maritimus* were growing at the uncultivated site in Ndiaye, and *A. raddiana* was growing at the uncultivated site at Fanaye.

Next, topsoil samples of the most extreme mineral fertilizer treatments with regard to nitrogen application (T0, T1 and T4) were analyzed for TSN, exchangeable and fixed nitrogen (Table 4). At both sites, exchangeable N ranged between 1.6 and 2.8% of TSN. Fixed N accounted for 5.5–8.2% of TSN, with slightly higher values in Fanaye. Treatment differences in N dose had no significant effect on these parameters.

The development of soil P in response to different P fertilizer doses was investigated by analyzing LTFE topsoil samples (Ndiaye) of all treatments from WS 1991 and WS 1997 on total P concentration and by analyzing all Ndiaye topsoil samples between installation and the WS 1997 on extractable phosphorus (P_{Bray1}). Comparison of total P concentration in the topsoil between 1991 and 1997 showed a significant reduction of total soil P for treatments without P application (T0 and T3; −50 mg P kg^{-1} soil), a small and not significant reduction for treatments with application of 26 kg P ha^{-1} (T1, T4 and T5; −17 mg P kg^{-1} soil), and a small and not significant increase for T2 (application of 52 kg P ha^{-1}; +18 mg P kg^{-1} soil). Estimating total quantity of soil P for the topsoil (0.0–0.2 m), using bulk densities of the respective horizons (see profile descriptions in Table 1), resulted in soil P losses of 149 kg P ha^{-1} for the treatments

Table 3
Soil reaction (pH), SOC, TSN and C/N ratio of samples from three different soil horizons at both LTFE sites (Ndiaye and Fanaye), 16 consecutive seasons after installation of the trial[a]

Site	Depth (m)	pH_{KCl}	SOC (%)	TSN (%)	C/N ratio
Ndiaye	0.0–0.2	5.6 a[b]	0.82 a[b]	0.080 a[b]	10.3 a[b]
Ndiaye	0.2–0.5	4.5 b	0.46 b	0.061 b	8.2 b
Ndiaye	0.5–0.7	4.2 b	0.38 c	0.050 b	8.0 b
Fanaye	0.0–0.2	6.1 b[b]	0.66 a[b]	0.054 a[b]	13.1 ns[b]
Fanaye	0.2–0.5	6.3 a	0.38 b	0.039 b	11.2 ns
Fanaye	0.5–0.7	6.0 b	0.39 b	0.036 b	12.0 ns

[a] Average values of all treatments are presented since no significant difference between treatments could be detected.

[b] At each site, results in a column followed by a common letter are not significantly different (ns) according to the Duncan’s multiple range test with $\alpha = 0.05$.

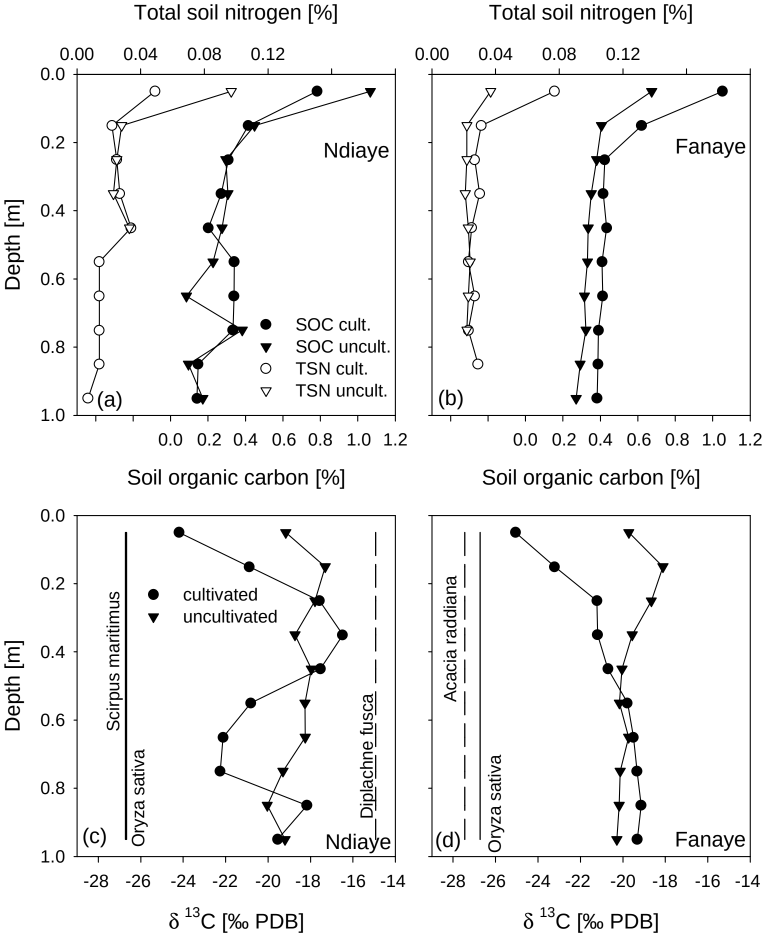

Fig. 2. Comparison of SOC, TSN and $\delta^{13}C$ in the profile between cultivated soils (treatment T3 in the LTFE) and adjacent uncultivated soils at Ndiaye ((a) and (c)) and Fanaye ((b) and (d)). In graph (c) and (d), $\delta^{13}C$ values for natural vegetation at each site as well as values for rice (*O. sativa*) are added. Legends in (a) and (c) are valid for (b) and (d).

Table 4

TSN, exchangeable N (N_{exch}) and fixed N (N_{fix}) for the treatments T0 (no mineral fertilizer application), T1 (120 kg N ha^{-1} per season), and T4 (180 kg N ha^{-1} per season) from samples of the top horizon (0.0–0.2 m depth) at both LTFE sites (Ndiaye and Fanaye), 16 consecutive seasons after installation of the trial[a]

Parameter	Ndiaye (0.0–0.2 m depth)			Fanaye (0.0–0.2 m depth)		
	T0	T1	T4	T0	T1	T4
TSN (mg kg^{-1} soil)	640	797	788 ns	508	620	478 ns
N_{exch} (mg kg^{-1} soil)	13	15	13 ns	12	15	13 ns
N_{fix} (mg kg^{-1} soil)	42	49	43 ns	38	41	39 ns
N_{exch} (% TSN)	2.1	1.9	1.6 ns	2.4	2.5	2.8 ns
N_{fix} (% TSN)	6.6	6.2	5.5 ns	7.5	6.6	8.2 ns

[a] At each site, treatment results in a row are not significantly different (ns) according to the Duncan's multiple range test with $\alpha = 0.05$.

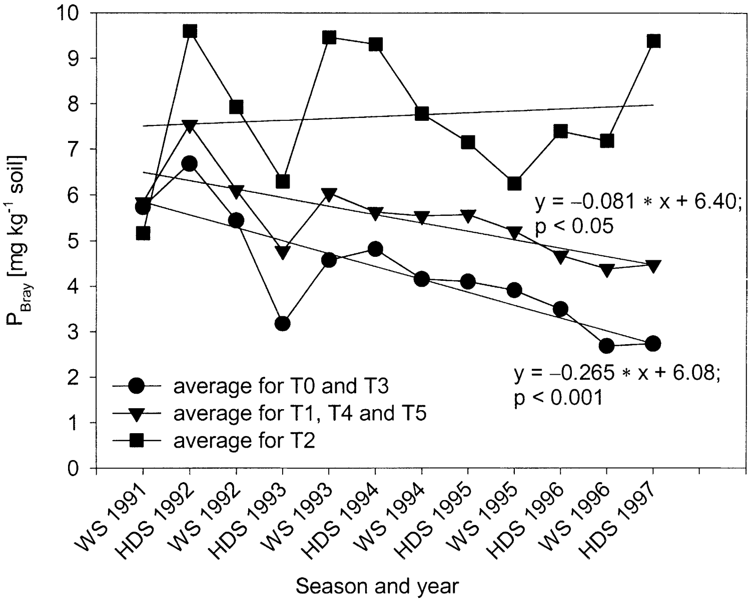

Fig. 3. Development of extractable phosphorus (P_{Bray1}) in the topsoil (0.0–0.2 m) of the LTFE in Ndiaye for different P-fertilizer treatments (T0 and T3: 0 kg P ha^{-1} per season; T1, T4 and T5: 26 kg P ha^{-1} per season; T2: 52 kg P ha^{-1} per season) and samples from the WS 1991 until the HDS 1997. Presented are average P_{Bray1} values for treatments with the same P-fertilizer dose according to results of the analysis of variance. Added are linear regressions for different P-fertilizer treatments. The regression for T2 was not significant.

without P application (T0 and T3) and in losses of 51 kg P ha^{-1} for the treatments T1, T4 and T5 (26 kg ha^{-1} per season P application). Estimated soil P increases for the treatment with application of 52 kg P ha^{-1} per season (T2) were 55 kg P ha^{-1}.

Analysis of variance for extractable P_{Bray1} showed a significant difference only for treatments with different P-doses. According to these results, treatments with the same P-dose were pooled for linear regression analysis (average P_{Bray1} values for these groups are presented in Fig. 3). Results show a significant decrease of P_{Bray1} for treatments without applied phosphorus (T0, T3: $P_{Bray1} = -0.265\,\mathrm{mg\,P\,kg^{-1}}$ per $+6.08$; $P < 0.001$) as well as for treatments where 26 kg P ha^{-1} per season were applied (T1, T4 and T5: $P_{Bray1} = -0.081\,\mathrm{mg\,P\,kg^{-1}}$ per season $+ 6.40$; $P < 0.05$). Extractable phosphorus in treatment T2 was highly variable and the regression was not significantly different from zero.

A comparison of seven different P fractions in two treatments of the LTFEs in Ndiaye and Fanaye is presented in Fig. 4. To identify the effect of P application on soil P pools, the treatments T2 (application of 52 kg P ha^{-1} per season) and T3 (no P application) were compared. Total P extracted was always higher in T2 than in T3, and ranged between 135 mg P kg^{-1} soil and 259 mg P kg^{-1} soil. In Ndiaye, P application caused a higher increase of extracted P in the subsoil (63 mg P kg^{-1} soil) than in the topsoil (39 mg P kg^{-1} soil), indicating a translocation of applied P. No transport in the profile seemed to occur in Fanaye, where P application increased total extracted P only in the topsoil (63 mg P kg^{-1} soil). In Ndiaye, applied P caused significantly higher P concentrations in the resin fraction, in the inorganic $NaHCO_3$ fraction and in the residual fraction. In Fanaye, increases were restricted to the resin fraction, the inorganic NaOH fraction and the HCl fraction. When estimating total amount of soil P from the surface to 0.5 m depth (using bulk densities shown in Table 1), T2 in Ndiaye contained about 1812 kg P ha^{-1} and T3 about 1395 kg P ha^{-1} (treatment difference is 418 kg P ha^{-1}). The same calculation in Fanaye resulted in 1119 kg P ha^{-1} for T2 and 942 kg P ha^{-1} for T3 (treatment difference is 177 kg P ha^{-1}).

To assess the impact of different potassium management strategies in the LTFE on soil potassium, LTFE topsoil samples from Ndiaye (WS 1991 and WS 1997)

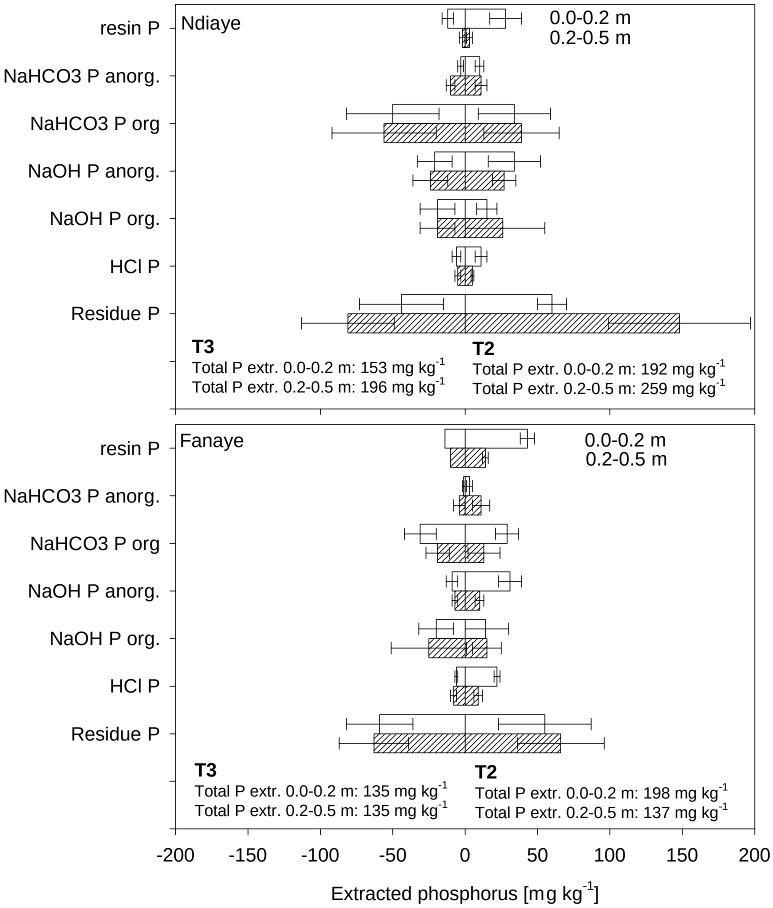

Fig. 4. Extracted phosphorus of seven different P fractions for the treatments T2 (application of 52 kg P ha^{-1} per season) and T3 (no P application) in the LTFEs at Ndiaye and Fanaye. Analyzed were samples from 0.0 to 0.2 m depth (white bars) and from 0.2 to 0.5 m depth (hatched bars). Horizontal bars represent the standard deviation.

were first analyzed for total K concentration. Analysis of variance did not show any significant difference of total K concentration in the topsoil between 1991 and 1997 (data not shown). Likewise, no significant effect on ammonium acetate exchangeable K (K_{exch}) could be found, but in T2 (application of 100 kg K ha^{-1} per season) a slight increase of K_{exch} was observed in 1997, whereas all other treatments showed slightly reduced K_{exch} in 1997.

To get further insight, a detailed analysis of different soil K pools for the two treatments with the most extreme K management (T2: 100 kg K ha^{-1} per season; T3: 0 K ha^{-1} per season) and WS 1999 samples from both sites was carried out. Results of the sequential extraction are presented in Table 5. Treatment 3 reduced K_{exch} in Ndiaye mainly in the topsoil, whereas in Fanaye K_{exch} was also reduced in the second soil horizon (0.2–0.5 m). Potassium extracted with cold 0.1 M HNO_3 followed the same trend, but total quantities were between 2 and 2.6 times higher than K_{exch}. Treatment T2 resulted in equal levels of K_{exch} in all three soil depths, but K extracted with cold HNO_3 was decreasing with increasing depth. The amount of K extracted with boiling 1 M HNO_3 was highest in the first extraction and declined steadily in subsequent extractions. Differences between the two treatments were most pronounced in the first two extractions with boiling HNO_3 and in Ndiaye mostly restricted to the topsoil. Amounts of K extracted with the first extraction were higher in Ndiaye (515–569 mg K kg^{-1} soil)

Table 5

Amount of potassium extracted with 1 M ammonium acetate, with cold 0.1 M HNO_3 and by repeated extractions with boiling 1 M HNO_3 from samples of three soil depths, two treatments (T2: 120 kg N ha^{-1}, 52 kg P ha^{-1}, 100 kg K ha^{-1}; and T3: 120 kg N ha^{-1}, 0 kg P ha^{-1}, 0 kg K ha^{-1}), and at both LTFE sites (Ndiaye and Fanaye), 16 consecutive seasons after installation of the trial

Site	Treatment	Depth (m)	NH_4OAc, 1.0 M (mg K kg^{-1} soil)	HNO_3, 0.1 M (mg K kg^{-1} soil)	HNO_3, 1.0 M; extraction number (mg K kg^{-1} soil)							Sum 1–7 (mg K kg^{-1} soil)
					1	2	3	4	5	6	7	
Ndiaye	T2	0–0.2	301	783	569	422	245	198	180	158	127	1899
Ndiaye	T3	0–0.2	260	639	517	356	244	201	172	135	122	1747
Difference			41	144	52	66	1	−3	8	23	5	152
Ndiaye	T2	0.2–0.5	321	717	550	369	220	199	176	147	127	1788
Ndiaye	T3	0.2–0.5	320	700	515	366	237	198	159	139	120	1734
Difference			1	17	35	3	−17	1	17	8	7	54
Ndiaye	T2	0.5–0.7	297	689	535	325	196	177	151	133	110	1627
Ndiaye	T3	0.5–0.7	315	726	533	332	213	179	156	129	111	1653
Difference			−18	−37	2	−7	−17	−2	−5	4	−1	−26
Fanaye	T2	0–0.2	235	506	476	315	227	195	182	169	157	1721
Fanaye	T3	0–0.2	171	361	422	305	212	176	169	154	149	1587
Difference			64	145	54	10	15	19	13	15	8	134
Fanaye	T2	0.2–0.5	235	466	443	303	213	177	167	159	146	1608
Fanaye	T3	0.2–0.5	192	397	413	285	208	172	173	150	148	1549
Difference			43	69	30	18	5	5	−6	9	−2	59
Fanaye	T2	0.5–0.7	213	417	410	281	205	169	171	158	145	1539
Fanaye	T3	0.5–0.7	204	398	411	293	206	179	174	159	149	1571
Difference			9	19	−1	−12	−1	−10	−3	−1	−4	−32

than in Fanaye (410–476 mg K kg^{-1} soil), but this relation was reversed for the last extraction (110–127 mg K kg^{-1} soil in Ndiaye, 145–157 mg K kg^{-1} soil in Fanaye).

Based on the extractions and using the definitions of Richards and Bates (1988), Haylock (1956) and Barber and Matthews (1962), four different K fractions were distinguished. Potassium extracted with 1.0 M NH_4OAc is defined as exchangeable K (K_{exch}), whereas all the other extracted K is defined as non-exchangeable K (Mactotal). The Mactotal fraction is further divided in a ‘‘moderately available K fraction’’ (StepK) and the ‘‘weakly available’’ CRK. Compared to Ndiaye, extracted CRK was higher in Fanaye and represented a bigger fraction of Mactotal than StepK (Table 6). In Fanaye, K depletion caused by T3 was significant in the two uppermost horizons and the K_{exch} and StepK fraction. Additionally, the CRK fractions in the topsoil were considerably reduced. In Ndiaye, differences of K fractions between treatments were statistically not significant, but highest differences with lowest P-levels (<0.26) were found in the K_{exch} and StepK fraction of the topsoil. Further considerable differences were observed in the CRK fraction, but the significance level was low. At both sites, K_{exch} constituted about 10% of total K extracted, StepK represented 48% in Ndiaye and 35% in Fanaye, and CRK represented 42 and 55% of total K extracted in Ndiaye and Fanaye, respectively.

From the quantities of K extracted in each horizon and the bulk densities of the respective horizons (see Table 1), quantities of K_{exch}, StepK and CRK were calculated per hectare (Table 7). Total quantities of K_{exch}, StepK and CRK from 0.0 to 0.5 m depth were estimated at 20 t K ha^{-1} (T2) and 19 t K ha^{-1} (T3) in Ndiaye, and 15 t K ha^{-1} (T2) and 14 t K ha^{-1} (T3) in Fanaye. Assuming, that the main treatment impact on the soil is limited to a depth of 0.5 m, T3 compared to T2 caused a decrease of exchangeable and non-exchangeable K of 1.22 t K ha^{-1} in Ndiaye and of 1.31 t K ha^{-1} in Fanaye. Based on total soil K concentrations, which were 1.22% at 0.0–0.2 m, 1.19% at

Table 6
Exchangeable K (K_{exch}), StepK, CRK and total amount of non-exchangeable K (Mactotal) in three different soil layers for two different fertilizer treatments (T2: 120 kg N ha^{-1}, 52 kg P ha^{-1}, 100 kg K ha^{-1}; and T3: 120 kg N ha^{-1}, 0 kg P ha^{-1}, 0 kg K ha^{-1}) and both LTFE sites (Ndiaye and Fanaye), 16 consecutive seasons after installation of the trial

Site	Parameter	Depth (m)	T2 (mg kg^{-1})	T3 (mg kg^{-1})	T2–T3 (mg kg^{-1})	*P*-level[a]
Ndiaye	K_{exch}	0–0.2	301	260	41	0.25
Ndiaye	K_{exch}	0.2–0.5	321	320	1	0.96
Ndiaye	K_{exch}	0.5–0.7	297	315	−18	0.61
Ndiaye	StepK	0–0.2	1296	1127	169	0.11
Ndiaye	StepK	0.2–0.5	1134	1139	−5	0.96
Ndiaye	StepK	0.5–0.7	1099	1140	−41	0.69
Ndiaye	CRK	0–0.2	1085	1000	85	0.53
Ndiaye	CRK	0.2–0.5	1050	977	73	0.60
Ndiaye	CRK	0.5–0.7	921	924	−3	0.98
Ndiaye	Mactotal	0–0.2	2381	2127	254	0.25
Ndiaye	Mactotal	0.2–0.5	2184	2116	68	0.76
Ndiaye	Mactotal	0.5–0.7	2020	2064	−44	0.83
Fanaye	K_{exch}	0–0.2	235	171	64	0.001
Fanaye	K_{exch}	0.2–0.5	235	192	43	0.01
Fanaye	K_{exch}	0.5–0.7	213	204	9	0.53
Fanaye	StepK	0–0.2	807	674	133	0.003
Fanaye	StepK	0.2–0.5	737	656	81	0.05
Fanaye	StepK	0.5–0.7	638	641	−3	0.93
Fanaye	CRK	0–0.2	1185	1102	83	0.10
Fanaye	CRK	0.2–0.5	1102	1098	4	0.93
Fanaye	CRK	0.5–0.7	1105	1124	−19	0.66
Fanaye	Mactotal	0–0.2	1992	1776	216	0.002
Fanaye	Mactotal	0.2–0.5	1839	1754	85	0.16
Fanaye	Mactotal	0.5–0.7	1743	1765	−22	0.70

[a] *P*-level of significance for the comparison of extractable K in each soil layer between treatment T2 and T3; Duncan's multiple range test with $\alpha < 0.05$.

0.2–0.5 m and 0.96% at 0.5–0.7 m in Ndiaye and 1.09% at 0.0–0.2 m, 1.03% at 0.2–0.5 m and 1.01% at 0.5–0.7 m in Fanaye, total soil K from 0.0 to 0.5 m depth was estimated at 93 t K ha^{-1} in Ndiaye and at 73 t K ha^{-1} in Fanaye.

4. Discussion

In the LTFE at Ndiaye, topsoil pH values increased significantly from 5.5 to about 6.5 and electrical conductivity was high and variable. Deckers et al. (1993) reported increasing pH, decreasing salinity and decreasing potential acidity resulting from irrigated rice cropping for a site close to Ndiaye with a similar soil. In this case, pH in the topsoil rose from 5.2 to 6.0 within 4 years and remained stable thereafter. At both sites, these developments can be attributed to the neutralization and leaching of salts and sulfidic materials present in the sub-soil. Reduced salinity due to rice cultivation and salinization due to fallow periods in the naturally saline Senegal River delta were also reported by Wopereis et al. (1998) and Ceuppens et al. (1997). The dominant processes controlling these developments are (i) salt leaching in flooded fields during the season and (ii) salt accumulation due to capillary rise from the shallow and saline water table in interseasons and fallow periods. Therefore, good irrigation and crop management are prerequisites for sustainability in this environment. In Fanaye topsoil reaction seemed to remain stable at values around 7 during the last few years, an observation confirmed by

Table 7

Estimation of total exchangeable K (K_{exch}) and non-exchangeable K (StepK and CRK) per hectare for two different fertilizer treatments (T2: 120 kg N ha^{-1}, 52 kg P ha^{-1}, 100 kg K ha^{-1}; and T3: 120 kg N ha^{-1}, 0 kg P ha^{-1}, 0 kg K ha^{-1}) at both LTFE sites (Ndiaye and Fanaye), 16 consecutive seasons after installation of the trial[a]

Site	Treatment	Depth (m)	K_{exch} (t ha^{-1})	StepK	CRK	Total
Ndiaye	T2	0–0.2	0.90	3.89	3.26	8.05
Ndiaye	T2	0.2–0.5	1.53	5.41	5.01	11.95
Ndiaye	T2	0.5–0.7	0.82	3.03	2.54	6.40
Ndiaye	T3	0–0.2	0.78	3.38	3.00	7.16
Ndiaye	T3	0.2–0.5	1.52	5.43	4.66	11.62
Ndiaye	T3	0.5–0.7	0.87	3.15	2.55	6.57
Difference	T2–T3	0–0.2	0.12	0.51	0.26	0.89
Difference	T2–T3	0.2–0.5	0.01	−0.02	0.35	0.33
Difference	T2–T3	0.5–0.7	−0.05	−0.11	−0.01	−0.17
Sum[b]	T2–T3	0–0.5	0.13	0.48	0.60	1.22
Fanaye	T2	0–0.2	0.64	2.21	3.25	6.10
Fanaye	T2	0.2–0.5	0.99	3.12	4.66	8.77
Fanaye	T2	0.5–0.7	0.63	1.89	3.27	5.79
Fanaye	T3	0–0.2	0.47	1.85	3.02	5.33
Fanaye	T3	0.2–0.5	0.81	2.77	4.64	8.23
Fanaye	T3	0.5–0.7	0.60	1.90	3.33	5.83
Difference	T2–T3	0–0.2	0.18	0.36	0.23	0.77
Difference	T2–T3	0.2–0.5	0.18	0.34	0.01	0.54
Difference	T2–T3	0.5–0.7	0.03	−0.01	−0.06	−0.04
Sum[b]	T2–T3	0–0.5	0.36	0.71	0.24	1.31

[a] In addition, the balance between both treatments for the depth from 0 to 0.5 m is presented. Calculations are explained in the text.

[b] Sum adds differences between treatments T2 and T3 only for the depth 0–0.5 m according to the assumption, that plants did not extract K from deeper horizons.

measurements and simulation studies at Fanaye by Samba (unpublished), but the limited number of observations from the LTFE does not allow any trend evaluation.

Comparison of SOC and TSN contents at the beginning of the LTFE in Ndiaye and after 16 consecutive seasons showed slightly lower average values in the topsoil for both parameters, but the difference was not significant. Comparison of SOC and TSN in cultivated and uncultivated soil profiles at Ndiaye (T3 in the LTFE and an adjacent uncultivated soil) also showed lower values in the topsoil for the cultivated site, but no statistic analysis was possible. Therefore, it cannot be concluded from the analyzed samples if topsoil SOC and TSN at Ndiaye did not change and the observed differences were due to spatial variability only or if SOC and TSN at Ndiaye are slowly declining due to intensive rice cropping. In the latter case, differences should become significant in several years and only then the question could be answered. The corresponding profiles in Fanaye showed higher SOC and TSN concentrations of cultivated soils. The possible influence of site-specific characteristics on the evolution of topsoil SOC and TSN is shown by analysis of several LTFEs in the humid tropics of Asia, which showed increases as well as decreases of SOM and TSN after introduction of highly intensive irrigated rice cultivation (De Datta et al., 1988; Cassman et al., 1995a). But in all these trials, treatments with fertilizer application always had higher SOM and TSN concentrations then unfertilized controls. The latter could not be confirmed in the here presented LTFEs. Additionally, N pool analysis in the LTFEs at Ndiaye and Fanaye did not show any influence of N fertilizer treatment on soil N pools (TSN, fixed and exchangeable ammonium).

Analysis of the $^{13}C/^{12}C$ isotope ratio was intended to study the impact of irrigation induced prolonged flooding on soil organic matter. Isotopic effects during anaerobic microbial breakdown of SOM to methane would have increased the $\delta^{13}C$ values in comparison to uncultivated soils. As $\delta^{13}C$ values of uncultivated sites were always higher than in cultivated soils, this process was obviously either not happening or it was overlain by a much stronger effect in the opposite direction. The profiles in uncultivated soils at Ndiaye and Fanaye showed very similar and homogenous $\delta^{13}C$ distributions with values between −18 and −20‰. This is even slightly higher than normal values of SOM originating from C3 plants and accumulated under anaerobic conditions ($\delta^{13}C$ values of −20 to −22‰ according to Scharpenseel and Neue, 1984; Nakamura et al., 1990). Additionally, neither the actual vegetation at Fanaye (*A. raddiana* with $\delta^{13}C$ values of −27‰) nor the shallow water table at Ndiaye had any clear influence on the $\delta^{13}C$ profile. It was therefore concluded that at both sites SOM throughout the profile is a mixture of material from C3 plants with average values around −27‰ and from C4 plants with average values of about −13‰ (Boutton, 1996). Many tropical Gramineae are C4 plants, which causes $\delta^{13}C$ values of −12 to −14‰ under tropical grasslands and savannas. Balesdent et al. (1988) reported topsoil $\delta^{13}C$ values of −18.6‰ for a native prairie soil under mixed vegetation (C3 and C4 species), which comes very close to values observed here. If methanogen microbes are active in the uncultivated soils cannot be decided from the $\delta^{13}C$ pattern.

Cultivation and organic residues from rice (a C3 plant) caused a decrease of the $\delta^{13}C$ signature, a process starting in the topsoil. Especially at Fanaye this development is clearly visible from the results. Penetration of rice organic matter into the soil reached a depth of about 0.5 m, which coincides approximately with the deepest cracks developing at this site during the interseason. In Ndiaye, rice organic matter penetrated to about 0.8 m, most possibly by infiltration of dissolved organic matter with the percolating soil solution. The high values in this profile from 0.3 to 0.5 m depth could be caused by prolonged water saturation from double cropping and related actual methanogenetic processes. Using the equations formulated by Cerri et al. (1985), the turnover of SOM since the trial establishment was estimated at about 50% for the topsoil at both sites. This rate is higher than those calculated from radiocarbon dating in temperate climates, but fits to results from warmer regions (Balesdent et al., 1987).

The influence of P fertilizer treatments on total soil P in the topsoil (0.0–0.2 m) was first evaluated for LTFE treatments in Ndiaye (samples from 1991 and 1997) with different fertilizer dose. Estimated phosphorus losses were only significant for T0 and T3 (no P application), and the calculated losses and gains were small compared to estimated balances from P export with grain and straw and P import from fertilizer application. Possible explanations were either P translocation into the subsoil and/or unknown P inputs from, e.g. irrigation water and dust deposition. Calculation and comparison of total soil P for the treatments T2 (52 kg P ha^{-1} per season applied) and T3 (no P application) based on total P extracted with the sequential extractions (0.0–0.5 m depth) confirmed P translocation into the subsoil at Ndiaye, but not at Fanaye.

Treatment trends of total soil P were confirmed by an evaluation of P availability in the topsoil at Ndiaye. Phosphorus availability was assessed with the P_{Bray1} test, which is suited for a wide range of soils under submerged conditions (Sanyal and De Datta, 1991). The results indicated a strong decrease of soil P availability for T0 and T3 (no P application), a medium decrease for T1, T4 and T5 (application of 26 kg P ha^{-1} per season), and a slight increase for T2 (application of 52 kg P ha^{-1} per season). Analyzing LTFE soil samples between 1991 and 1997 with the P_{Bray1} test revealed, that the test results were very variable between years although most treatments at a given sampling date reacted in a similar way (Fig. 3). This indicated that P availability measured with P_{Bray1} extractions seemed to depend strongly on the sampling conditions, which questions the usefulness of this test for the systematic evaluation of soil P supply in irrigated systems. Similar observations by Bolland et al. (1989) question the assumption of a constant relationship between the P_{Bray1} test and yield.

Soil P fractionation was conducted to characterize soil P pools in the soils at Ndiaye and Fanaye, to evaluate the behavior of applied mineral P fertilizer, and to observe the impact of highly negative P balances. Total soil P extracted in the topsoil (0.0–0.2 m) ranged between 153 and 192 mg P kg^{-1} soil at Ndiaye and between 135 and 198 mg P kg^{-1} soil at Fanaye. These values are about 20% lower than P concentration measured four seasons earlier by X-ray fluorescence spectroscopy, but both analyses show the same trend. Compared to topsoil values (0.0–0.15 m) compiled by Cross and Schlesinger (1995), these are very low P concentrations. They found between 400 and 700 mg P kg^{-1} soil for less weathered soils (Entisols, Inceptisols, Aridisols, Vertisols, Mollisols) and the soils at Ndiaye and Fanaye are in the same range as strongly weathered soils (200 mg P kg^{-1} soil in Spodosols and Ultisols). According to Cross and Schlesinger (1995), weathering induces a reduction of the relative pool sizes (compared to total soil P) of HCl extractable P and increases of the NaOH fraction and the organic P fraction. Compared to P fraction distributions summarized by these authors, unfertilized plots in Ndiaye and Fanaye (T3) were characterized by high values for the organic P fraction (36% of total P in Ndiaye, 45% of total P in Fanaye), medium values for the NaOH fraction (6% of total P in Ndiaye, 8% of total P in Fanaye), and low values for the HCl fraction (4% of total P in Ndiaye, 5% of total P in Fanaye). Again, this indicated strong weathering of the here analyzed soils. At both sites, these results are in contrast to other soil characteristics typical for less weathered soils, like high base saturation, predominance of Ca and Mg at the exchange complex, and a considerable percentage of three layer clay minerals. Therefore, a strong weathering of the soil in situ must be excluded, leaving low content of primary P minerals in the parent material as the only explanation for the low P status of the soils at both sites. The domination of strongly weathered soils in the regions supplying the Senegal River sediments, could be responsible for the low P concentration observed. Low P status of floodplains is a general feature in the Sahel and Sudan savanna (Buri et al., 1999).

Comparison of treatments with and without P application does not allow separating effects of P application and plant P uptake, but the combined effect of both factors caused higher P concentration in the resin and the residual fraction in T2 in Ndiaye. In Fanaye, higher values for T2 were observed in the resin fraction, the inorganic NaOH fraction and the HCl fraction. The combined effect of both factors (increase with P application and decrease due to plant uptake) on the resin fraction was repeatedly reported (e.g. Schmidt et al., 1996; Guggenberger et al., 1996; Zhang and MacKenzie, 1997; Pheav et al., 2003), but the effect on other fractions is less universal. Additional effects on the $NaHCO_3$-fraction and the NaOH fraction were reported by Schmidt et al. (1996), effects on organic and residual P were found by Hedley et al. (1982b) and Guggenberger et al. (1996), and according to Zhang and MacKenzie (1997) and Pheav et al. (2003) almost all fractions were affected. The significant differences and trends detected by the P_{Bray1} extraction for treatments with differing P application as described above, is most possibly related to the effect of P fertilization on the P resin fraction.

Application induced increase of the residual P fraction in Ndiaye was limited to the subsoil, where simultaneously the percentage of pedogen iron oxides increased sharply from 30% in the topsoil to 44% in the subsoil (0.2–0.5 m). Most probably, a substantial part of fertilizer P was occluded in Fe-oxides and thereby directly transformed to residual P. Differences in total P content between treatments T2 (with P application) and T3 (without P application) were restricted to the topsoil in Fanaye, whereas they could be observed to 0.5 m depth in Ndiaye. This indicated again, that transport of dissolved elements with percolation was more important in Ndiaye than in Fanaye.

Comparison of total soil K in the topsoil of the LTFE at Ndiaye before installation of the trial and after 13 seasons did not show any significant depletion or enrichment. This could be explained by the rather small depletion effect in the LTFE relative to the high total soil K concentration. Application of 100 kg K ha^{-1} per season (T2) resulted in slightly increased exchangeable K, whereas all other treatments had slightly reduced values, but none of these differences was significant. However, it indicated that T2 at least maintained the original soil K status. The same conclusions resulted from K pool analysis for this treatment at both LTFE sites. K extracted with NH_4OAc, with 0.1 M HNO_3 as well as with boiling 1 M HNO_3 increased from the subsoil (0.5–0.7 m) to the topsoil (0–0.2 m), and none of the K pools analyzed showed distinct signs of preferential enrichment or depletion due to plant uptake or K application. This suggests, that applied K is distributed between different K pools by equilibrium reactions, and can enter exchangeable and non-exchangeable K pools (Richards and Bates, 1988). Estimation of the K balance based on K import from K application and K export with straw and grain, resulted in only minor K losses for treatment T2.

When no K was applied and K removal was considerable due to medium yields and complete straw and grain removal (T3), soil K depletion was clearly detectable. Plant K uptake reduced soil K pools in Fanaye in the topsoil as well as in the subsoil (0.0–0.5 m), and was more restricted to the topsoil (0.0–0.2 m) in Ndiaye. This can be explained by lower soil K reserves in Fanaye and/or by restricted root depth due to high subsoil salinity in Ndiaye. The results from Fanaye show that the subsoil can contribute considerably to K nutrition of irrigated rice plants (about 30% of total K depletion in T3 at Fanaye). This is in contrast to considerations by Cassman et al. (1995b), who assumed that the subsoil does not contribute significant nutrient amounts due to low root densities.

Soil K pools analyzed were exchangeable K, ‘‘moderately available K’’ (StepK), and ‘‘weakly available’’ CRK according to definitions of Richards and Bates (1988), Haylock (1956), and Barber and Matthews (1962). The assumed availability expressed in these terms was questioned by the observed K depletion patterns in T3 at Ndiaye and Fanaye. At both sites, quantity of K pool depletion in the topsoil was in the order StepK > CRK > K_{exch}. But it should not be overseen, that the observed K depletion pattern developed cumulative in 16 seasons. The exchangeable K used by the rice crop in each season will be replenished from non-exchangeable pools after each season by equilibrium reactions. Therefore, the cumulative depletion pattern observed cannot be used to decide which K fraction was actually used by the plant. Nevertheless, a considerable contribution of non-exchangeable K to K nutrition of irrigated rice during the season is likely (see also Cassman et al., 1995b; Dobermann et al., 1996a,b) and the presented results show that even the CRK fraction was used by plants, either directly or indirectly via equilibrium reactions.

Comparison of total extracted K in T2 and T3 from 0.0 to 0.5 m depth was used to estimate losses due to double cropping without K application (16 seasons). The difference between both treatments was 1.2 and 1.3 t ha^{-1} in Ndiaye and Fanaye, respectively. The losses constituted a considerable part of total extracted K (about 6% at Ndiaye and about 9% at Fanaye), but total extracted K constituted only about 20% of total soil K at both sites. Total soil K levels found at both sites are not exceptional for soils with mixed composition of clay minerals (two and three layer minerals) (Helmke and Sparks, 1996; Sharpley, 1990), but total K extracted was high compared to values reported by Richards and Bates (1988) (between 640 and 1350 mg K kg^{-1} soil compared to 1780 and 2380 mg K kg^{-1} soil observed here). This confirms Buri et al. (1999), who reported high available soil K levels in West Africa flood plains in the Savanna zones.

5. Conclusions

It remains an open question, whether the described evolution of SOC, TSN and SOM characteristics in the LTFEs can be taken as indicators for sustainability of irrigated rice cultivation in the Sahelian environment or not. The analysis of the data from one site (Ndiaye) indicated a decreasing trend for SOC and TSN, but the results were not significant and only further monitoring can clarify this matter. But even if a decline of SOC and/or TSN occurs, this does not necessarily signify an equal change of indigenous soil N supply, as can be concluded from the weak relation between these parameters in field surveys. Surprising was the strong effect of the trial on the carbon isotope ratio of SOM and the estimated SOM turnover rate, especially because rice straw was continuously removed from the plots. These results indicate that SOM quality changes due to a changed ‘‘cropping’’ system could be relatively rapid, but the effects on SOM quality in the analyzed trials remained unclear.

Soil analyses of P and K pools indicated only small changes when these elements were applied at medium quantities (26 kg P ha^{-1} and 50 kg K ha^{-1}). In contrast, treatments with N but without P and/or K application showed considerable soil P and soil K depletion. Therefore, rice cultivation without P and/or K application cannot maintain soil fertility, although the respective treatments represent extreme cases in comparison to farmer's practice (in general characterized by lower cropping intensity, lower average yields and only partial straw removal). The nutrient depletion process is relatively quick for P due to the naturally low P status of soils in the Senegal River region, whereas the high soil K reserves buffer even important negative K balances for decades. These results are representative for intensive irrigated rice-based systems in most regions of the West African Sahel and Sudan savanna. Low soil N and P and relatively high soil K status are general features of floodplains in the Sahel and Sudan savanna. Only from the oldest irrigation schemes in the region (e.g. the Office du Niger in Mali) more widespread K deficiency and significant positive fertilizer response to K application were reported. It is therefore concluded that irrigated rice cultivation in the region mostly maintains the soil nutrient status since most farmers apply P doses similar to the medium doses in the LTFE, have lower cropping intensities and average yields and do not remove all the rice straw from their fields.

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