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Effect of straw application on rice yields and nutrient availability on an alkaline and a pH-neutral soil in a Sahelian irrigation scheme

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Abstract

Like elsewhere in the Sahel, actual rice yields (3–5 t ha^{-1}) are far below yield potential ($\pm$8 t ha^{-1}) in an irrigation scheme in central southern Mauritania. Earlier studies showed that yields are especially low on alkaline soils due to N and P deficiency. We investigated the potential of rice straw application as a mean to improve yields and fertilizer efficiency on an alkaline soil (pH 8.2) and a pH-neutral soil (pH 6.2). Application of 5 t straw ha^{-1} increased yields by 1.1 t ha^{-1} on average, independent of soil type and fertilizer dose. Contrary to our study, similar studies in Asia showed little short-term effects of straw on yield and N uptake. Straw application improved N availability, but not P availability. The improved N availability was attributed to N mineralized from the straw, from increased mineralization of soil organic matter (SOM) with a low C:N ratio (<7.2) and from increased mineral fertilizer N (urea) recovery efficiency. We deduced that improved N fertilizer recovery upon straw application was due to reduced nitrification–denitrification losses. On the alkaline soil, volatilization was important, but that process seemed unaffected by straw application. We hypothesize that the positive effects of straw application at our study site are due to low soil C content (<43 g kg^{-1}) and low C:N ratio compared to most lowland rice soils in Asia.

Introduction

The Foum Gleita irrigation scheme in southern Mauritania is one of many Sahel schemes developed to improve food security after the droughts in the 1970s and 1980s. Rice (*Oryza sativa* L.) is the dominant crop in these irrigation schemes. Actual yields are often low (3–5 t ha^{-1}) and far from yield potential (7–10 t ha^{-1}), which raises questions about the economic viability of the costly irrigation schemes in this region (Bélières et al. 1995). There is an urgent need to improve productivity while keeping input costs low. Van Asten et al. (2003) concluded that nutrient deficiencies largely contribute to low yields in Foum Gleita, with N being the primary and P the secondary nutrient constraint. However, mineral fertilizers make up about 20% of the total production costs for rice farmers in the Sahel (Donovan et al. 1999). Productivity problems are more pronounced on alkaline (pH 7.5–8.5) than on pH-neutral soils. Soil N and P supply and fertilizer recovery efficiency of nitrogen (REN) and of phosphorus (REP) are much lower on the alkaline soils (REN = 0.26; REP = 0.13) than on the pH-neutral soils (REN = 0.40; REP = 0.22) (van Asten et al. 2003). We hypothesize that volatilization and P immobilization cause poor fertilizer recovery on alkaline soils, since these processes become more important with increasing carbonate levels and pH.

This study evaluates rice straw as an inexpensive soil amendment to improve fertilizer recovery efficiencies. At present, most farmers burn their rice straw, except at the end of the dry season (DS) when some straw is used as cattle fodder. The effect of rice straw incorporation on soil quality, nutrient uptake, and rice yields has been studied over a wide range of soil and climatic conditions. Based on separate literature reviews, Ponnamperuma (1984) and Dobermann and Fairhust (2000) concluded that the initial yield increase due to straw incorporation over straw burning or removal is minimal (<0.5 t ha^{-1}), but that yield increases with time, as soil fertility improves. However, their conclusions were mainly based on findings in neutral to acidic lowland soils in Asia. On an alkaline soil in India, incorporation of 10 t ha^{-1} straw increased yields from 3.4 to 5.2 t ha^{-1} (Chatterjee et al. 1979).

Straw may improve the recovery efficiency of applied mineral N fertilizer. Microbial organisms that decompose the straw can act as a N sink (immobilization) when straw is incorporated shortly before transplanting (Witt et al. 2000). However, the immobilization is temporary. A few weeks to months later, decomposing microbial organisms will act as a nutrient source (Ponnamperuma 1984; Witt et al. 2000). At the time of the 1st urea application, root systems are still small, and a large part of the mineral N in the soil and surface water may be lost due to leaching, denitrification and volatilization. If part of the mineral N is immobilized and released later, when plant roots have reached a maximum uptake capacity, then the overall N losses might be reduced (Olk et al. 2000). Straw application may further improve N availability through a reduction of volatilization losses as a result of a drop in surface water pH. Glissmann and Conrad (2000) and van Bodegom and Scholten (2001) observed that anaerobic decomposition led to high concentrations of organic acids in the soil solution. We hypothesize that when these organic acids diffuse to the surface water layer, they may reduce the pH and hence, volatilization losses.

Straw application may also influence phosphorus availability. As a P source, straw is not important due to its low P content and due to temporary P immobilization by microbial organisms in the early stages of decomposition. However, straw can indirectly improve P availability through dissolution of Fe- and Ca-bound P under flooded conditions (Dobermann and Fairhust 2000). The release of Fe-bound P largely depends on the soil's redox level (Eh), while the dissolution of Ca-bound P depends on the soil's pH and pCO_2. Chorom and Rengasamy (1997) found that fresh organic matter application enhanced the decrease in both Eh and pH of submerged calcareous–alkaline soils. Therefore, we hypothesize that plant-available P increases when straw is applied.

From the above, we hypothesize that straw application leads to increased plant N and P availability through direct (nutrient source) and indirect (reduced losses) effects, and that these effects are different on alkaline and pH-neutral soils. The extent of these beneficial effects and their impact on yield can be quantified through effects on nutrient uptake, REN, and REP. The objectives of this study were to (i) quantify the effect of straw amendments on yield, nutrient uptake and fertilizer recovery on alkaline and pH-neutral soils, and (ii) to identify the processes that explain the effect of straw on yield, nutrient uptake and fertilizer recovery. To reach our objective, we conducted a series of field and pot trials.

Materials and methods

Site description

Foum Gleita (16°08′ N, 12°46′ W) has a typically Sahelian climate with erratic rainfall (250 mm yr^{-1}) between July and October and an annual average air temperature of 30 °C. The irrigation scheme was built in 1984 and a large dam allows for gravimetric irrigation throughout the year. The irrigation water quality varies throughout the year (pH 7.5–8.3 and EC 0.10–0.25 dS m^{-1}) as a function of rainfall and evaporation.

The alkaline soils are found on the upper and middle slopes and have formed *in situ* from the schist parent material (<0.8 m). The soil contains very little phosphorus (P_{Bray1} = 2.6 mg kg^{-1}). The pH-neutral soils (>1.2 m) are found further down slope on the lower slopes, river banks, and depressions. These soils have a partly alluvial origin and contain more phosphorus (P_{Bray1} > 4.4 mg kg^{-1}) (van Asten et al. 2003). In both soils, organic carbon% and C:N ratio are low (Table 1).

Field straw trials

The objective of the field trial was to quantify the effect of straw amendments on yield and fertilizer recovery efficiency in N and P deficient conditions. Researcher-managed straw trials were conducted in the 2000 and 2001 dry seasons on both an alkaline and a pH-neutral soil, but the 2001 trial on the alkaline soil failed to produce good harvest data due to excessive bird damage. Rice variety IR-13240-108-2-2-3, in Mauritania known as Sahel 108, was used. The treatments were based on four levels of fertilizer dose (N and P) and two levels of straw application (S), as follows: T1 = control; T2 = N; T3 = N + 1/2P; T4 = N + P; T5 = control + S; T6 = N + S; T7 = N + 1/2P + S; T8 = N + P + S. According to earlier findings (van Asten et al. 2003), treatments T1 and T5 would primarily result in N deficient conditions, while treatments T2, T3, T6 and T7 would lead to different levels of P deficiency.

Table 1. Soil characteristics of the top horizon (0–20 cm) and average straw nutrient content in the field straw trails on the alkaline and pH-neutral soil.

	Alkaline	pH-neutral
Texture class[a]	SiCL	L
$pH_{1:2.5}$	8.2	6.2
$EC_{1:5}$[dS m^{-1}]	0.17	0.06
$CaCO_3$ [g kg^{-1}]	4.0	< 0.5
CEC [$cmol_c$ kg^{-1}]	14.8	11.0
ESP [%]	18.0	1.5
C [g kg^{-1}]	4.3	4.0
N total [g kg^{-1}]	0.6	0.7
C:N ratio	7.2	5.7
N_{STRAW} [g kg^{-1}]	4.4	5.4
P_{STRAW} [g kg^{-1}]	0.4	1.0
N in 5 t straw [kg]	22	27
P in 5 t straw [kg]	2	5

[a]FAO (1990)(SiCL = silty clay loam; L = loam).

Treatments were repeated three times in a randomized block design. The total N fertilizer (urea) dose was 175 kg ha^{-1} applied in three split applications (40% three weeks after transplanting, 40% at panicle initiation and 20% at heading). The P fertilizer dose was 26 kg ha^{-1} and the 1/2P dose was 13 kg ha^{-1}, applied as basal application in the form of triple super phosphate (TSP). The straw (5 t dry matter ha^{-1}) was incorporated loosely into the topsoil 3 days before transplanting, which coincided with soil tillage practices.

Rice and straw yields were estimated from a 6 m^2 harvest area and a 12 plant subsample in the center of each 25 m^2 plot. Concentrations of N in grain and straw at maturity were determined using the micro-Kjeldahl method (Bremner 1996). Plant phosphorus concentrations were measured using the method of Yoshida et al. (1976). Total N and P uptake were estimated from the N and P concentrations of straw (N_{STRAW}, P_{STRAW}) and grain (N_{GRAIN}, P_{GRAIN}), multiplied by the respective straw and grain yield. Since N was the primary and P, the secondary nutrient constraint, soil N supply was estimated from total N uptake in T1 and soil P supply was estimated from the total P uptake in T2. Straw N supply was estimated as the difference in N uptake between T5 and T1, and straw P supply was similarly calculated using the difference in P uptake between T6 and T2, respectively. Fertilizer recovery efficiencies (i.e. REN and REP) were calculated as the additional nutrient uptake (total nutrient uptake minus soil and straw nutrient supply) following fertilizer application divided by the inorganic fertilizer dose.

Pot straw trial

The objectives of the pot trials were (i) to identify the processes that led to the low REN, REP, and soil N and P supply on the alkaline soils, and (ii) to evaluate how straw amendments would affect those processes.

A large topsoil (0–0.3 m) sample from an alkaline soil in Foum Gleita was brought to the WARDA station in Saint Louis. The sample was air-dried and homogenized before being transferred to plastic 10 l polypropylene buckets (Ø 25 cm). The trial consisted of the following 14 treatments varying in fertilizer application (NP), straw application (S) and the presence of a plastic cover (C): P, NP, N, 1/2NP, PC, NPC, 1/2NPC, PS, NPS, NS, 1/2NPS, PSC, NPSC, and 1/2NPSC, where P = 26 kg P ha^{-1}, N = 175 kg N ha^{-1}, 1/2N = 87.5 kg N ha^{-1}, S = 5 t straw ha^{-1}, and C = pot covered with transparent plastic and acidification of the floodwater to a pH between 6.0 and 7.0. Each treatment was replicated 3 times. The 42 pots were distributed randomly over two large concrete basins. Pots were saturated with water 5 days before transplanting. Three 30-day-old rice seedlings of IR-12340-108-2-2-3 (Sahel 108) were transplanted into each pot to mimic the soil micro-environment of irrigated rice. Space between pots was filled with earth and the basin was flooded to ensure the same soil and water temperatures (30 °C) for all pots. Straw and TSP granules were mixed into the wet topsoil 3 days before transplanting.

To evaluate the importance of volatilization, C treatment pots were covered with transparent plastic directly after the first N application. In addition, floodwater pH in covered pots was maintained low (pH 6.0–7.0) using 0.1 M HC1 to suppress volatilization (Mikkelsen 1987). In the middle of the covered pots a 10 cm high PVC tube (Ø 12.5 cm) was inserted into the soil (2 cm deep), through which the plants could grow. The floodwater inside the PVC tubes was covered with a layer of small polystyrene foam balls in order to diminish gas-exchange between the water surface and the atmosphere. PVC tubes were also placed in non-covered treatments to avoid bias. In order to allow the monitoring of the flood water quality, a round hole (Ø 1 cm) was made in the plastic cover that was closed with a rubber stopper. Irrigation water originated from the Senegal River. Its alkalinity was increased up to 1.5 mmol l^{-1}, using Na_2CO_3, in order to mimic average irrigation water quality in Foum Gleita. Pots were irrigated daily to maintain constant water levels. In order to avoid excessive salt stress, the floodwater in the pots was renewed at 2, 25 and 45 days after transplanting (DAT). The flood water pH, EC and temperature were measured daily (at 9.00 am and 3.00 pm) in all pots, Concentrations of NH_4^+ in the floodwater of all treatments were monitored at 1, 3, 5 and 7 days after N application. The NH_4^+ samples were taken at 9.00 am and stored at 4 °C in airtight polypropylene bottles (20 ml), after acidification to pH < 2.0 with concentrated HCl. Concentration of NH_4^+ was determined by the salicylate method (Nelson 1983). Floodwater NO_3^- concentrations of N and NS treatments were monitored after the 2nd N application using a Skalar (SA-40) continuous-flow analyzer.

One of our objectives was to quantify the effect of straw on plant available P in a range of P deficient conditions (i.e. when N fertilizer is applied). We monitored plant available P using resin capsules (UNIBEST, Inc., Bozeman MT). Each capsule contained 2.2 $mmol_c$ of cation + anion exchange capacity and had a total surface area of 11.4 cm^2. The process of absorption by the resins is considered to mimic important exchange, solubilization, and transport processes occurring in the rice rhizopshere (Dobermann et al. 1997). Soil samples of the N, NP, NS and NPS treatments were taken at 0, 32 and 92 days after transplanting (DAT). Each sample was split into three subsamples and transferred into airtight polypropylene bottles. A resin capsule was inserted into each subsample and the bottles were stored for incubation in a dark place. Resin capsules were removed from a first series of subsamples after 1 day of incubation. The same procedure was repeated after 7 and 14 days of incubation. P was extracted from the resin capsules using HCl as an extractant (Dobermann et al. 1997).

Statistical analysis

Statistical analyses were conducted using the software package SPSS for Windows (Version 10.0). Significance of site, fertilizer and straw application factors and their interactions on yield, fertilizer recovery efficiencies and plant nutrient concentrations from the field trials were analyzed for each season using a multiple factorial ANOVA. Means for yields were compared using least square difference (LSD) test. Means for P_{RESIN} were compared with the LSD test following a one-way ANOVA on different treatments. Significance of the cover, nitrogen and straw application factors and their interactions on NH_4^+ peak concentrations of floodwater in the pot trials after the 2nd and 3rd urea applications were analyzed using a multiple factorial ANOVA. An one-tailed student *t*-test was used to compare NO_3^- concentrations in the pot trial floodwater.

Results

Yield, REN and REP in the field trial

Figure 1 shows yields for each soil type×season combination. Plant height and tiller number were higher in straw amended plots of all trials (data not shown) from early tillering onwards. Both fertilizer dose (NP) and straw application (S) showed significant effects ($P < 0.001$) on yield at both sites in the 2000 DS, but the straw effect was not significant ($P = 0.09$) in the 2001 DS. There was no significant NP × S interaction in any of the trials, nor was there any S × soil type interaction in the 2000 DS trials; i.e. the yield increasing effect of straw was independent of fertilizer dose and soil type. Straw application (S) had a significant positive effect on N_{STRAW} and N_{GRAIN} concentrations ($P < 0.05$) in all trials. Fertilizer dose (NP) also had a significant ($P < 0.05$) effect on N_{GRAIN} in all trials. In addition, NP and NP × S interaction were significant ($P < 0.05$) for N_{STRAW} on the pH-neutral soil in the 2001 DS trial. On the alkaline soils, N_{STRAW} (3.8–5.7 g kg^{-1}) and N_{GRAIN} (7.1–9.8 g kg^{-1}) were significantly ($P < 0.001$) lower than N_{STRAW} (4.2–7.6 g kg^{-1}) and N_{GRAIN} (8.0–12.3 g kg^{-1}) on the pH-neutral soil. Nitrogen uptake and REN were significantly ($P < 0.001$) higher on the pH-neutral soil (on average 0.10–0.31 kg kg^{-1}), than on the alkaline soils (Table 2). On both soils, both the applications of P ($P < 0.001$) and straw ($P = 0.013$) significantly improved REN values, but neither season nor any of the interactions were significant.

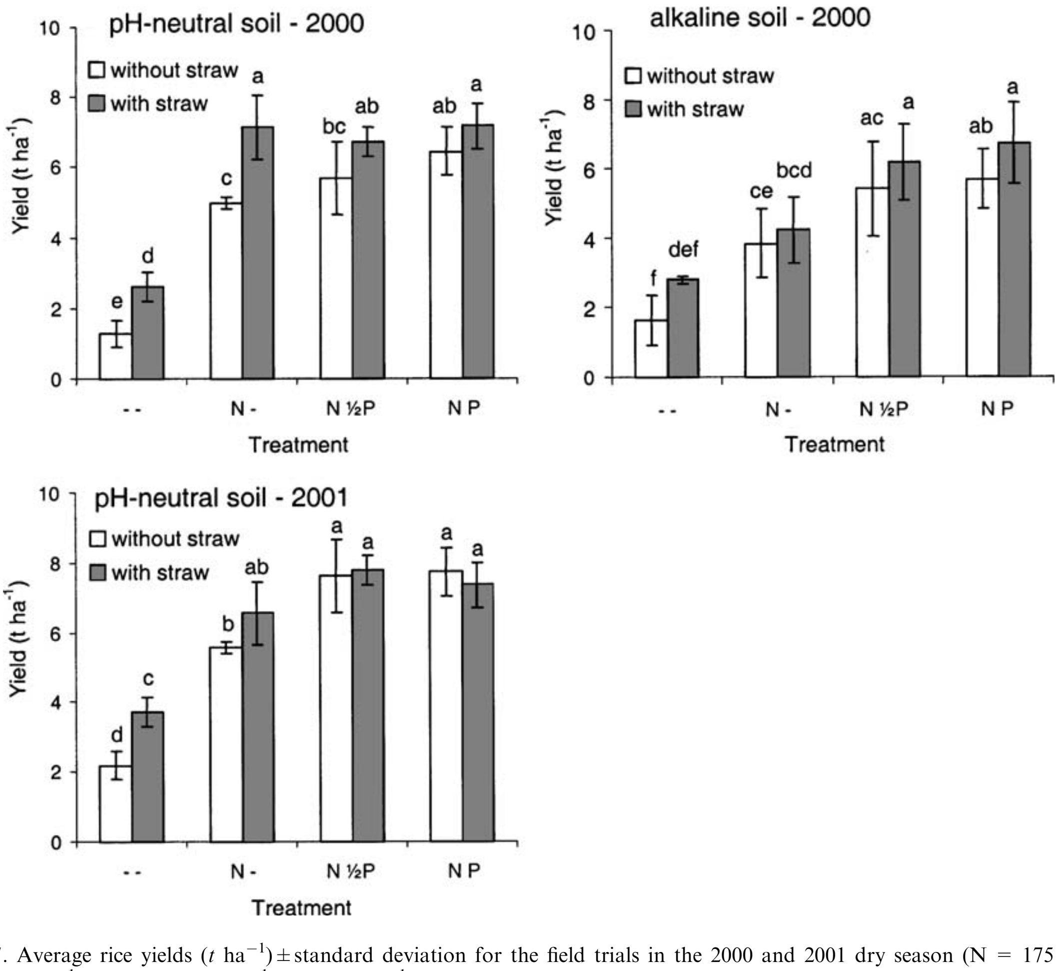

Figure 1. Average rice yields (t ha^{-1}) ± standard deviation for the field trials in the 2000 and 2001 dry season (N = 175 kg ha^{-1}; P = 26 kg ha^{-1}; 1/2P = 13 kg ha^{-1}; S = 5 t ha^{-1} fresh straw) on the alkaline and pH-neutral soil. Letters signify differences (P < 0.05) between treatment for LSD-test.

Table 2. Average N uptake (kg ha^{-1}) and recovery efficiency of applied Urea-N (kg kg^{-1}) for the field trials in the 2000 and 2001 dry season. (N = 175 kg ha^{-1}; P = 26 kg ha^{-1}; 1/2P = 13 kg ha^{-1}; S = 5 t ha^{-1} fresh straw).

	T1	T2	T3	T4	T5	T6	T7	T8
	Control	N	N + 1/2P	N + P	Control + S	N + S	N + 1/2P + S	N + P + S
Dry season 2000								
pH-neutral soil								
Uptake	21	78	94	94	39	106	109	130
Recovery efficiency	–	0.33	0.42	0.42	–	0.38	0.40	0.52
Alkaline soil								
Uptake	20	55	75	66	33	63	86	107
Recovery efficiency	–	0.20	0.32	0.26	–	0.17	0.30	0.42
Dry season 2001								
pH-neutral soil								
Uptake	27	84	103	112	36	120	134	140
Recovery efficiency	–	0.32	0.43	0.49	–	0.48	0.56	0.59

Table 3. Average P uptake (kg ha^{-1}) and recovery efficiency of applied TSP-P (kg kg^{-1}) for the field trials in the 2000 and 2001 dry season. (N = 175 kg ha^{-1}, P = 26 kg ha^{-1}; 1/2P = 13 kg ha^{-1}; S = 5 t ha^{-1} fresh straw).

	T1	T2	T3	T4	T5	T6	T7	T8
	Control	N	N + 1/2P	N + P	Control + S	N + S	N + 1/2P + S	N + P + S
Dry season 2000								
pH-neutral soil								
Uptake	6	18	22	24	10	22	22	28
Recovery efficiency	–	–	0.29	0.21	–	–	0.05	0.25
Alkaline soil								
Uptake	4	8	11	11	6	8	13	17
Recovery efficiency	–	–	0.22	0.10	–	–	0.40	0.35
Dry season 2001								
pH-neutral soil								
Uptake	6	18	27	30	11	21	26	31
Recovery efficiency	–	–	0.67	0.45	–	–	0.39	0.37

Straw application had no significant effect ($P > 0.05$) on P_{STRAW} in either soil, but fertilizer dose did ($P < 0.05$). P_{STRAW} on the alkaline soil was 0.2–0.3 g kg^{-1} in treatments that received N in combination with no or half the P dose, and 0.4–0.6 g kg^{-1} in treatments that received full P dose. Trends were similar on the pH-neutral soil, but P_{STRAW} was significantly higher (0.07–0.13 g kg^{-1}). Straw application increased P uptake and REP on the alkaline soil but decreased it on the pH-neutral soil (Table 3), resulting in a significant straw×soil type interaction ($P = 0.03$). Residual effects of the P fertilizer application in 2000 on the subsequent trials were not taken into account and led to increased REP values for the pH-neutral trial in 2001.

Monitoring soil and water chemistry changes in the pot trial

Straw amendments had little effect on the floodwater pH. The early morning (9.00 am) readings for non-acidified pots are shown in Figure 2. The afternoon (3.00 pm) measurements showed a very similar pattern, but pH values were about 1 pH unit higher for treatments with P fertilizer application and 0.3 pH unit higher for treatments without P fertilizer application (data not shown).

Temporal dynamics of floodwater NH_4^+ concentrations are presented in Figure 3. Ammonium concentrations after the first urea application were only measured from day 5 onward, due to technical problems. Peak NH_4^+ concentrations after

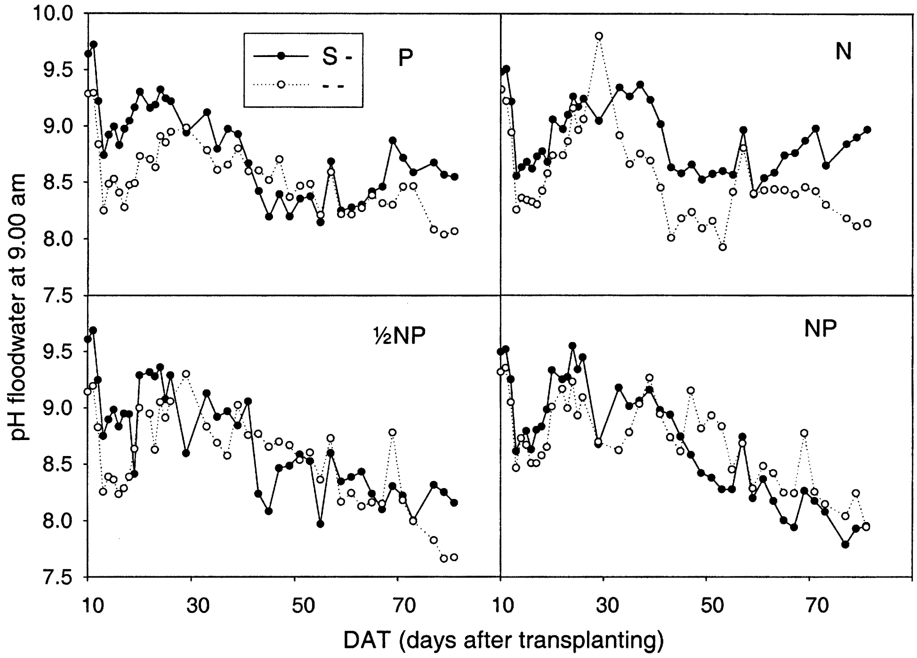

Figure 2. Evolution of floodwater pH of non-covered treatments in the pot trials: S = 5*t* straw ha^{-1}; N = 175 kg ha^{-1}; 1/2N = 87.5 kg ha^{-1}; P = 26 kg ha^{-1}.

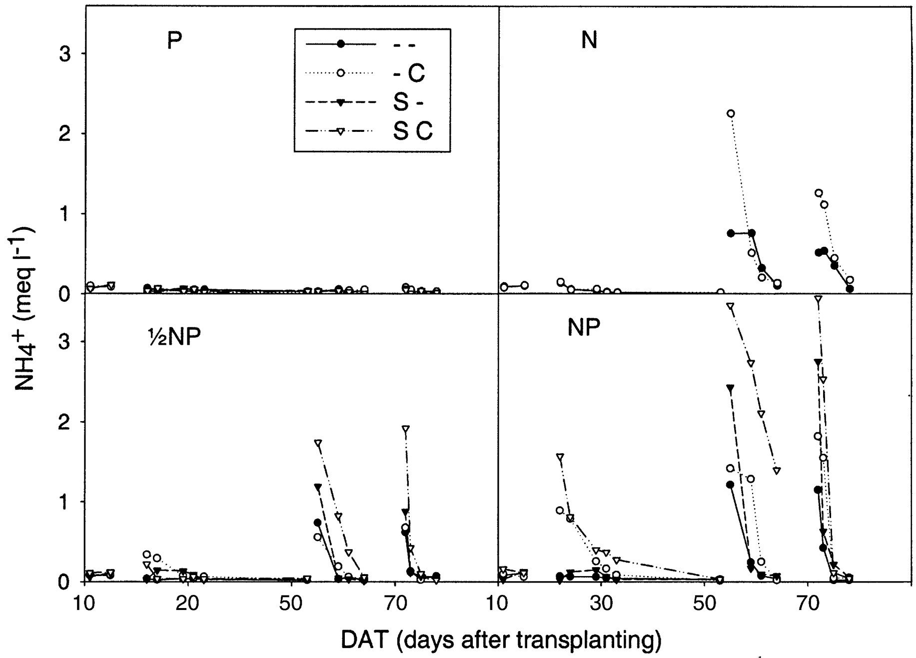

Figure 3. Floodwater NH_4^+ concentrations for treatments in the pot trials; S = 5*t* straw ha^{-1}; C = cover, N = 175 kg ha^{-1}; 1/2N = 87.5 kg ha^{-1}; P = 26 kg ha^{-1}.

the second and third fertilizer application showed very similar trends; i.e. N, C, S factors and N × C, N × S and C × S interactions all had significant (P < 0.05) effects on NH_4^+ concentrations. Ammonium peak concentrations in treatments that received N fertilizer decreased in the following order; SC > S- > -C > - -. Floodwater NO_3^- concentrations for the treatments N and NS varied little during the first 15 days after the second N application, but average concentration in the N treatment (0.063 mmol NO_3^- l^{-1}) was significantly higher ($P < 0.05$) than in the NS treatment (0.026 mmol NO_3^- l^{-1}).

The incubation time (1, 7 and 14 days) had no significant effect on the P absorbed on the resin capsules (P_{RESIN}). In Figure 4, P_{RESIN} values are shown for 0, 32, and 92 DAT and 7 days incubation. At 0 DAT, no differences between the treatments were found. At 32 DAT, P_{RESIN} in the NP treatments was significantly higher ($P < 0.001$) than in the N, NS and NPS treatment. At 92 DAT P_{RESIN} in the NP and NPS treatments was significantly higher ($P < 0.05$) than in treatments N and NS.

Discussion

In the 2000 DS field trials, the application of straw increased yields by an average of 1.1 t ha^{-1}, independent of soil type or fertilizer dose. In the 2001 DS, a similar yield increase (1.3 t ha^{-1}) was observed, except for treatments that received both N and P fertilizer on the pH-neutral soil. Actual yields of the latter treatments approached the potential (± 8 t ha^{-1}) (van Asten et al. 2003), so no further yield increase could be expected.

On both soils, application of 175 kg N ha^{-1} significantly increased yields. Adding P fertilizer further increased yields, most notably on the alkaline soil. This indicates the occurrence of an N–P-colimitation. The plant P concentrations and

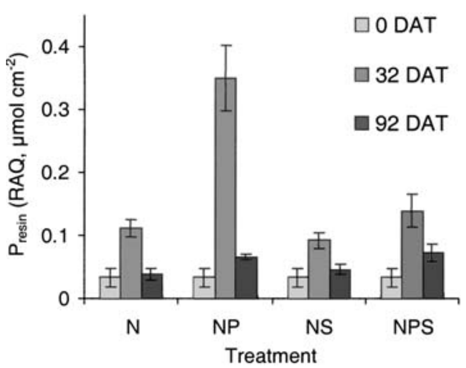

Figure 4. Mean $P_{RESIN} \pm$ standrad deviation at 0, 32 and 92 days after transplantation and 7 days incubation period; expressed in resin adsorption quantity (RAQ).

P uptake confirm that P deficiency is more important on the alkaline soil; i.e. P_{STRAW} on the alkaline soil was below the deficiency level (0.6 g kg^{-1}) (Dobermann and Fairhust 2000) and particularly low (0.2–0.3 g kg^{-1}) for treatments that received no P fertilizer. The outcome of the field trials was similar to findings of van Asten et al. (2003), who concluded that P deficiency was a major constraint in Foum Gleita, especially on the alkaline soils when N but no P fertilizer was applied.

Under P deficient conditions (application of N, but no P fertilizer) on both soils, P uptake did not significantly increase when straw was applied. The effect of straw on REP was negative for the pH-neutral soils, and only slightly positive for the alkaline soil. Resin capsule measurements in the pot trials suggested negative effects of straw application on P availability in the alkaline soil. During the vegetative growth period (32 DAT), P_{RESIN} in treatments that received P fertilizer was markedly lower when combined with straw application. Hence, we found no evidence to support our hypothesis that straw applications increases P availability through increased solubilization of Fe or Ca-bound P in the soil, On the contrary, the resin capsule measurements suggest a decrease in P availability during the first week after straw application, presumably due to microbial immobilization. We conclude (i) that P deficiency is an important yield-limiting factor, especially on the alkaline soils, and (ii) that straw amendments do not improve P availability on either of the soils studied.

Given the significant yield increases on both soil types unrelated to improved P availability, the question arises as to what extent the yield increases by straw application were caused by improved N availability. In treatments that received no fertilizer, straw application increased plant N uptake by 13 kg ha^{-1} on both soil types. This equals about half the N applied through straw application. It is very unlikely that the increased N uptake originates solely from N mineralized from the straw, considering that Takahashi et al. (2003) found that only 23–24% of N in the rice straw had been mineralized in both lowland and upland conditions after 90 days. In addition to the N released upon mineralization, we suspect that part of the soil N became available for plant uptake. The C:N ratio (<7.2) of the Faun Gleita soils is low and in the range commonly found for soil microbiota (Reichardt et al. 2001). This indicates that microbial breakdown of soil organic matter (SOM) is primarily carbon limited. The application of crop residues with a high C:N ratio would provide soil microbes the necessary energy to mineralize part of the N-rich SOM.

Treatments that received both N and P fertilizer had similar yields on both soils. Although plant N concentrations indicated that N was limiting at both sites, plant N concentrations, N uptake and REN were all much lower on the alkaline soil than on the pH-neutral soil. Nonetheless, increases of yield, N uptake, and REN upon straw application were very similar on both soils. In treatments that received the full N and P dose, straw application increased N uptake by 35 kg ha^{-1} on average, which largely exceeds the N content of the applied 5 t straw ha^{-1}. The increased N uptake was also expressed in the REN, which increased by 0.10–0.16 kg kg^{-1} for NP treatments on both soils. So, apart from additional release of indigenous soil N, the recovery of added fertilizers was increased by straw application.

We hypothesized that volatilization losses caused poor fertilizer recoveries under unamended conditions. This would be especially true for the alkaline soils due to their high pH and the presence of calcite (Singh and Nye 1986). Indeed, floodwater pH in the pot trials (pH 7.5–10.5) was high enough to support substantial NH_3 volatilization losses (Reddy and Patrick 1984). We observed consistently higher NH_4^+ concentrations in the floodwater of C treatments, which confirmed the suppression of volatilization (Chen et al. 1998) and underlined the importance of volatilization losses on the alkaline soils. We also hypothesized that the application of straw could decrease volatilization losses through temporal microbial immobilization of N, and that this process would be more important on the alkaline than on the pH-neutral soil. Hence, the N buffering effect of straw and the subsequent reduction in N loss and increase in REN should be higher on the alkaline soil than on the pH-neutral soil. However, we did not observe this. Thus, the field trials provided no evidence that supported the hypothesis of decreased volatilization due to temporal microbial N-immobilization. Neither did floodwater measurements in the pot trial provide evidence for reduced volatilization upon straw application. On the contrary, application of straw increased NH_4^+ in the floodwater, while floodwater pH in non-covered straw treatments remained as high as in non-straw treatments. This suggests an increase in NH_3 volatilization rate in straw treatments. Bouldin et al. (1991) reported that increased urea hydrolysis with straw application (Sahrawat 1983; Gill et al. 1999; Pattnaik et al. 1999) resulted in increased floodwater NH_4^+ concentrations and enhanced NH_3 volatilization losses. Furthermore, if volatilization decreased as a result of straw application, we should have observed a negative interaction for the factors $C \times S$ on NH_4^+ peak concentrations, but the increase in NH_4^+ peak concentrations upon straw application was equal or higher in C treatments when compared to the no C treatments. Therefore, we reject the hypothesis that the application of straw improves N availability through a decrease in NH_3 volatilization losses. This conclusion is in line with studies by Tian et al. (2001) and Gill et al. (1999) who found that application of rice straw had no effect and a promoting effect on NH_3 volatilization losses, respectively.

If straw application does not decrease volatilization losses, then what process improved REN on both soils? The answer may be found in the floodwater NH_4^+ measurements of the pot trial. The changes in NH_4^+ concentrations in the floodwater after the second and third N application showed similar patterns, i.e. both straw and cover significantly increased peak NH_4^+ concentrations. At 3–5 days after the second and third N application, NH_4^+ concentrations in S treatments were no longer higher than those in treatments that received no S. We attribute the higher NH_4^+ peak concentrations in the S treatments to commonly observed increased hydrolysis of the applied urea. Hence, depletion of the applied urea was much more rapid in the rice straw amended soil. A more rapid hydrolysis would lead to higher NH_4^+ peak concentrations initially, but would leave less urea for conversion to NH_4^+ later on (i.e. day 3–5), When we translate this to the straw and no straw treatments, it would mean that we expect NH_4^+ peak concentrations to be higher for the straw treatments, but the peak would be of shorter duration when compared to the no straw treatments. In other words, floodwater NH_4^+ concentrations should initially be lower, but later on be higher in the no straw treatments when compared to the straw treatments. However, after the initial NH_4^+ peak concentration (day 1–3), floodwater NH_4^+ in the straw treatments decreased to levels equivalent to, and not lower than, the NH_4^+ concentrations in the non-straw treatments (day 5–7). A plausible explanation is that the floodwater NH_4^+ concentration in the straw treatments remained relatively high due to decreased nitrification–denitrification losses.

It is generally agreed that the rate of denitrification is controlled by the rate of nitrification in flooded soils (e.g. Rao et al. 1984). Nitrification–denitrification is an important N fertilizer loss mechanism in irrigated rice. Although estimates vary widely, most authors find losses of 10–60% of applied N (Reddy and Patrick 1984; Reddy et al. 1990; Aulakh et al. 2001). We have good reason to believe that nitrification–denitrification losses are very high in Foum Gleita. Firstly, low to moderate REN indicates that substantial losses of applied N occur on both alkaline and pH-neutral soil. Secondly, both soils contain little organic carbon (<4.3 mg kg^{-1}) and have low C:N ratios (<72). Microbial activity is therefore C-limited. In incubation trials, the CO_2-production rate was 4–5 times lower on Foum Gleita's alkaline soil compared to some of Asia's most-studied rice soils (i.e. Mahaas, Gapan, Bugallon, Luisiana and Pila) (van Bodegom, unpublished results). As a result, nitrifying bacteria would suffer little from oxygen competition with microbiota that decompose organic matter. Therefore, high nitrification rates could be sustained in the no-straw treatments. However, application of fresh organic matter increases the competition for oxygen. Bacteria that aerobically break down organic matter out-compete nitrifying bacteria for the limited amount of oxygen in the flooded soil (Focht and Verstraete 1977). Increased oxygen competition would lead to a decrease in nitrification rate, and consequently decreased nitrification–denitrification losses. Adhya et al. (1996) showed that the nitrification potential of samples from green-manure amended plots was significantly lower than from control plots in a rice soil. The lower floodwater NO_3^- concentrations in S treatments are in line with this hypothesis, although the latter may also be attributed to higher denitrification rates as a result of rice straw application (Rochester and Constable 2000). To verify whether the positive effect of straw on N availability is related to decreased nitrification–denitrification, further research should be conducted using ^{15}N-labeled urea.

On initial examination, it seems surprising that straw had similar effects on yield and REN on two soils that showed large differences in pH, calcite content, and soil nutrient supply. However, most of the straw effect on yield and REN could be attributed to reduced nitrification–denitrification losses and increased N mineralization from SOM. These processes are driven by C% and C/N ratios, which were similar for both soils.

Conclusions

In Foum Gleita, the application of rice straw has a strong positive effect ($\approx$1.1 t ha^{-1}) on rice yields, independent of fertilizer dose and soil type. This is in contrast to most Asian rice soils that show little short-term effects of rice straw application on yield. The yield increase is caused by increased availability of N, not P. Increased N availability is likely due to N mineralized from the straw and increased N mineralized from SOM, which has a low C:N ratio. Furthermore, the application of straw increased recovery efficiency of applied urea-N. The improved REN by straw application could not be attributed to a decrease in volatilization losses, although the latter appears to be a major N loss mechanism on the alkaline soil. We attributed the improved REN to reduced nitrification–denitrification losses. Nitrification is expected to play an important role in these soils, given their low C% and low C:N ratio and relatively low mineralization rates. This results in low competition for oxygen and favors large nitrification–denitrification losses. Much more than in most Asian rice soils, application of fresh straw will lead to a relative large increase of the soil's C% and C:N ratio. Straw amendments will stimulate microbial activity and increase oxygen competition. A decrease in available oxygen will slow down nitrification and subsequently limit nitrification–denitrification losses. We hypothesize that rice straw has similar effects on yield and REN on other rice soils with similarly low C% and C:N ratio. Farmers in Foum Gleita can use rice straw as a cheap alternative to increase yields and profitability on the short term, independent of their mineral fertilizer management and soil type.

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