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Field Crops Research 72 (2001) 1–15

Field Crops Research

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Efficient phosphorus application strategies for increased crop production in sub-Saharan West Africa

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Received 15 December 2000; received in revised form 17 April 2001; accepted 25 April 2001

Abstract

Comparable data are lacking from the range of environments found in sub-Saharan West Africa to draw more general conclusions about the relative merits of locally available rockphosphate (RockP) in alleviating phosphorus (P) constraints to crop growth. To fill this gap, a multi-factorial field experiment was conducted over 4 years at eight locations in Niger, Burkina Faso and Togo. These ranged in annual rainfall from 510 to 1300 mm. Crops grown were pearl millet (*Pennisetum glaucum* L.), sorghum (*Sorghum bicolor* (L.) Moench) and maize (*Zea mays* L.) either continuously or in rotation with cowpea (*Vigna unguiculata* Walp.) and groundnut (*Arachis hypogaea* L.). Crops were subjected to six P fertiliser treatments comprising RockP and soluble P at different rates and combined with 0 and 60 kg N ha^{-1}. For legumes, time trend analyses showed P-induced total dry matter (TDM) increases between 28 and 72% only with groundnut. Similarly, rotation-induced raises in cereal TDM compared to cereal monoculture were only observed with groundnut. For cereals, at the same rate of application, RockP was comparable to single superphosphate (SSP) only at two millet sites with topsoil pH-KCl < 4.2 and annual average rainfall > 600 mm. Across the eight sites NPK placement at 0.4 g P per hill raised average cereal yields between 26 and 220%. This was confirmed in 119 on-farm trials revealing P placement as a promising strategy to overcome P deficiency as the regionally most growth limiting nutrient constraint to cereals.

Keywords: Crop rotation; Fertiliser placement; Legumes; Millet; Rockphosphate; Soil fertility

1. Introduction

Low levels of soil phosphorus (P) and nitrogen (N) are the major constraints to crop growth on nutrient-depleted sandy soils of sub-Saharan West Africa above 400 mm annual rainfall (Bationo et al., 1992, 1993, 1998a,b; Poulain et al., 1974). The low surface coverage with plants enhances the deleterious effects of wind and water erosion on topsoil productivity and further contributes to negative nutrient balances at the watershed level. These are reported to reach 15 kg N, 2 kg P and 15 kg K ha^{-1} yr^{-1} for the predominantly agro-pastoral land-use systems of this region (Buerkert and Hiernaux, 1998; Stoorvogel and Smaling, 1994). Application of soluble P fertilisers and locally available rockphosphates (RockPs) can enhance organic carbon (Corg) fixation in the agro-ecosystem and improve crop yields (McClellan and Notholt, 1986; Roesch and Pichot, 1985). On a strongly acid soil with 600 mm average rainfall RockP application was almost as effective as single superphosphate (SSP) in increasing yields of pearl millet (*Pennisetum glaucum* L., Bationo et al., 1990). Nevertheless, the

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0378-4290/01/$ – see front matter
PII: S0378-4290(01)00166-6

application of mineral fertilisers regardless of their type, to rainfed staple crops in Sudano–Sahelian West Africa remains below 5 kg ha^{-1} yr^{-1} (van Reuler and Prins, 1993). In an effort to increase fertiliser use efficiency and to reduce investment costs to cash-poor, subsistence-oriented farmers, P placement has been advocated as an effective technique to increase crop growth (Bationo et al., 1998a,b; Buerkert and Hiernaux, 1998). Localised fertiliser application seems a promising strategy in this environment where planting densities for hand-planted millet under on-farm conditions average at 5000 hills ha^{-1} (McIntire, 1986). In previous studies seed placement of 13 kg P ha^{-1} as SSP resulted in only limited yield gains compared to broadcast applications of the same amount (Christianson et al., 1990). This was attributed to rapid water depletion in the dense root zone around the placed fertiliser. Subsequent work with seed coating equivalent to 100 g P ha^{-1} showed large early placement effects on millet growth that, however, decreased to a mere 10% yield advantage at final harvest (Rebafka et al., 1993a). The purpose of this paper was to draw more general conclusions about the effectiveness of broadcast and placed application of soluble P and RockPs in alleviating P deficiency to cereals under the low-input conditions of sub-Saharan West Africa. To this end a multi-year experiment was conducted on benchmark sites in the Sahelian, Sudanian and Guinean zone of this region. Using time trend analysis, the results of this experiment were summarised and interpreted over the 4 years of its duration and in view of the large differences in site-specific edaphic, climatic and plant species-dependent properties.

2. Materials and methods

2.1. Multi-factorial experiment

2.1.1. Sites

From 1995 to 1998 multi-factorial trials were conducted under rainfed conditions on Psammentic Paleustalfs in the Sahelian zone of Niger at Banizoumbou (13°31′N, 2°39′E), Sadoré (13°14′N, 2°17′E), Kara Bedji (13°15′N, 2°32′E) and Goberi (12°58′N, 2°50′E), on an Arenic Kandiustalf in the Sudanian zone of Niger at Gaya–Bengou (11°59′N, 3°32′E) and on a Haplustalf in the Sudanian zone of Burkina Faso at Fada (11°59′N, 0°19′E). From 1996 to 1999 the experiment was extended to the northern Guinean zone of Togo on an isohyperthermic Plinthic Kanhaplustult at Koukombo (10°17′N, 0°23′E) and an isohyperthermic Plinthustalf at Kaboli (8°45′N, 1°35′E). The chosen sites covered a wide range of edaphic and climatic conditions with a single growing season of 4–6 months (Table 1). Soils in the Sahelian zone were derived from eroded and re-deposited sand dunes, ranged in pH-KCl between 4.1 and 4.5, had

Table 1
Mean annual precipitation and initial soil chemical parameters at 0–0.2 m depth for eight sites in West Africa in May 1995 (data from Buerkert et al., 2000)

Site	Precipitation[a] (mm)	pH[b]	Clay (g kg^{-1})	Corg (mg kg^{-1})	P-Bray I (mg kg^{-1})	P-water[c] (μg kg^{-1})	Ca^{2+} (cmol kg^{-1})	CEC[d] (cmol kg^{-1})	BS[e] (%)	N$_{min}$ (mg kg^{-1})
Banizoumbou	510	4.4	50	1.50	1.5	300	0.4	0.8	74	5
Sadoré	560	4.5	30	2.26	2.8	440	0.4	1.1	86	n.a.[f]
Kara Bedji	590	4.2	40	1.57	1.9	130	0.2	0.8	56	4
Goberi	600	4.1	30	1.55	1.7	280	0.2	0.8	50	2
Gaya	800	4.2	130	3.30	2.5	140	0.4	1.3	66	9
Fada	850	5.4	150	5.20	1.3	320	1.8	2.8	99	3
Koukombo	1100	5.6	50	3.67	2.0	1100	1.3	1.9	97	12
Kaboli	1300	4.7	160	6.46	3.8	1250	1.3	3.3	71	18

[a] Average annual rainfall for 5–10 years.
[b] pH in 0.01 M KCl (1:2.5).
[c] P-water determined after Sissingh (1971) but with incubation time reduced to 5 min at a soil:water ratio of 1:10.
[d] Effective cation exchange capacity.
[e] Base saturation.
[f] Not available.

between 30 and 50 g kg^{-1} clay, varied in Corg content between 1.5 and 2.3 mg kg^{-1}, were poorly aggregated and showed only little evidence of macro-organisms. Soils in the Sudano–Guinean zone, in contrast, were much higher in pH, had about three times more clay and Corg and appeared well aggregated (Table 1). With increasing amounts of total annual rainfall, these heavier soils were also characterised by clay and silica movement and showed strong evidence of termite activity. At all sites, trials were laid out in a split-plot design with completely randomised mainplots of $10 \times 10\,m^2$ size.

2.1.2. Mainplots

Six P fertiliser treatments and two levels of N were factorially combined and replicated twice in each trial. Crop residues (CR) were broadcast in all plots at traditional farmers' level (500 kg ha^{-1}) in January of each year, the middle of the dry season. Phosphorus treatments consisted of (i) a control without P (P0); (ii) annual broadcast P applied at 13 kg ha^{-1} as SSP (SSP13); (iii) broadcast P applied once for 3 years as high quality ('soft') Tahoua RockP at 39 kg ha^{-1} (TRockP39); (iv) annual hill-placement of 4 kg P ha^{-1} ($P4_{placed}$) as ground SSP in 1995 and 1996 and as ground NPK fertiliser (15–15–15) in 1997, 1998 and 1999; (v) TRockP39 combined with $P4_{placed}$ and (vi) broadcast P applied once for 10 years as TRockP at 130 kg P ha^{-1} (TRockP130) combined with $P4_{placed}$. Despite generally higher TDM production in the wetter zones and differences in the cereal species sown, P levels were kept constant to facilitate the comparison of treatment effects on crop growth and soil properties across environments. To study residual effects of broadcast P application, in the fourth year annual P was reapplied only in treatment $P4_{placed}$. Due to space constraints at Sadoré, P was only applied at the first four levels. Nitrogen, applied as calcium ammonium nitrate (CAN) at 0 and 60 kg N ha^{-1} was split into three equal applications, which were made after emergence, at thinning and at booting.

2.1.3. Subplots

The following four cropping systems were randomly assigned as 5 m × 5 m wide subplots to each of the 32 mainplots: continuous cereal, both phases of the cereal/legume rotation and a cereal–legume intercrop. Of these treatments, only the first three were considered in the analyses reported here, because the cereal–legume intercrop followed local practices and changed over years. In the Sahelian and the Sudanian zone of Niger, the cereal sown was millet at 10 000 hills ha^{-1}, in Burkina Faso sorghum was sown at 40 000 hills ha^{-1} and in Togo maize at 53 330 hills ha^{-1}. Typically hills comprised three plants for millet and one plant for sorghum and maize. The legume sown at all sites in Niger was cowpea at 40 000 hills ha^{-1}; at Fada, Koukombo and Kaboli groundnut was sown at 55 550 hills ha^{-1}. The choice of the legume species depended on farmers' preference in the predominant local cropping system. Legumes were sown after the rainy season was well established, usually 20–30 days after the cereal. At harvest, the hills of each plot, with the exception of border rows, were cut and dry weight of grain, heads and remaining straw were determined at 65°C to compute total dry matter (TDM). Plant TDM rather than grain yield was chosen as output variable because (i) this parameter was less affected by rainfall distribution, pest and diseases and (ii) both straw and grain are of similarly high value within the integrated crop-livestock systems of the region. Further details about the crop husbandry were reported by Bagayoko et al. (2000b).

2.1.4. Statistical analysis

Each plot in an experiment provided a time series of 4 years. Simple linear regressions of crop TDM versus year were used to assess trends on a plot basis. Regression slopes were then subjected to analysis of variance. This procedure, also known as two-stage or derived variable analysis, appropriately handles autocorrelation in longitudinal data (Diggle et al., 1994).

In cereal legume-rotation plots, cereal yield data were only produced every second year. For these plots, cereal data from both subplots (different phases) within a mainplot were merged to obtain a full time series of cereal yield data for the rotation over 4 years. These were denoted as Y1, Y2, Y3 and Y4. The same approach to obtain 4 years of data was followed in legumes. The regression slope for a time series (SLOPE in kg ha^{-1} yr^{-1}) was used as a response variable in a subsequent analysis of variance for each of the eight trials. Regression slopes were also computed when an observation in the series was missing. Since only very few data were missing, no adjustment was deemed necessary. Subsequently, the regression was used to derive two variables, that is the predicted yield in the first and the fourth year (P1 and P4). These predictions were used to graphically display regression trend lines. Yield data were pooled across N and cropping systems whenever these factors did not show statistically significant effects ($P < 0.05$).

The analysis of a trial for the derived variable SLOPE proceeded in two steps. First, the full model was fitted using the GLM procedure of the SAS System (SAS Institute, 1990). Non-significant terms ($P > 0.05$) were dropped, subject to the marginality requirement that lower order effects were retained despite non-significance if a corresponding higher-order term was significant (Nelder, 1994). Since P fertiliser treatment was the main factor of interest, the main effect for this factor was generally retained even if non-significant. In the second step, the reduced model was used for computing treatment means. The model selected for the derived variable SLOPE was used also to analyse the derived traits P1 and P4. The main purpose of these analyses was to generate graphical displays showing the time trend for different factor levels. A scatter was displayed around the trend lines with points given by least square means for the original data (Y1, Y2, Y3 and Y4) based on separate analyses for the 4 years using the same linear model as that selected for SLOPE. All graphs contain least significant differences ($\mathrm{LSD}_{0.05}$) for the vertical distance between regression lines in the first and fourth year. This LSD is based on the relevant standard error of a difference from the REML analysis of the derived variables P1 and P4. Multiple mean comparisons were conducted and displayed as described by Piepho (2000a,b).

For cereals the full and reduced models were formulated with the following explanatory variables (for legumes there was no cropping system factor).

2.1.5. Variables

P = mineral P rate (0 = P0; 1 = SSP13; 2 = TRockP39; 3 = TRockP39 + $\mathrm{P4}_{\mathrm{placed}}$; 4 = $\mathrm{P4}_{\mathrm{placed}}$; and 5 = TRockP130 + $\mathrm{P4}_{\mathrm{placed}}$), N = mineral N rate (0 = N0; 1 = N60), SYSTEM = cropping system (1 = continuous cereal 2 = rotation cereal / legume).

2.2. On-farm testing of P placement

2.2.1. Treatments and sites

In 1998 a total of 120 Nigerien farmers in the Maradi, Dosso and Say regions were co-operating to test P placement effects under on-farm conditions. Each farmer was asked to choose a piece of millet land and to divide it into two parts similar in size, cropping history and average natural productivity. One part served as a control without mineral fertiliser (P0), the other received 0.4 g P applied as 6 g of ground NPK (15–15–15) fertiliser placed together with the seed in each hill at sowing ($\mathrm{P4}_{\mathrm{placed}}$). At 10 000 hills ha^{-1}, this was equivalent to 4 kg P ha^{-1}, but farmers' densities averaged to about half of that. Farmers were allowed to use the cultivar, sowing density and management practices, such as crop residue or manure application and number of weeding operations, of their choice provided that both plots were treated the same. In 1999 similar on-farm trials were conducted with different farmers in the region of Say, southern Niger, which included a third treatment consisting of placed diammonium phosphate (18–46–0, DAP) application at 0.4 g P per hill. This treatment was added because prices per unit of P applied were more advantageous than for NPK; it also allowed to examine the relative role of N versus P in the observed fertiliser placement effects under farmers' conditions.

2.2.2. Data and risk analysis

In both years local collaborators recorded grain yields for each farmer by sampling at least 100 m^2 in both plots. After discarding data from farmers who did not follow the agreed upon rules, the final data comprised 91 pairs of grain yields in 1998 and 28 sets in 1999 coming from fields varying in size between 400 and 5000 m^2. For each year, these data were sorted according to the magnitude of the control plot yields and presented as a scatter plot.

Both data sets were also used to assess the relative risk of the $\mathrm{P4}_{\mathrm{placed}}$ treatment compared to farmers' current practice, the unfertilised treatment P0. To this end, for each farm the yield mean (MEAN), defined as $[\frac{1}{2}(\mathrm{P4}_{\mathrm{placed}} + \mathrm{P0})]$, was computed as a soil productivity index. Risk analysis was based on net returns per treatment. Since the main interest was in treatment differences, only the return and cost factors differing among treatments were taken into account. These were: grain yield (kg ha^{-1}); grain price = 60 FCFA[1] kg^{-1}; fertiliser price = 150 FCFA kg^{-1}; amount of fertiliser = 30 kg NPK ha^{-1}; child wage for placed P application at sowing = 500 FCFA per day; time for placed P application = 1.7 days ha^{-1}. This information was used to compute DIFF (= net return $\text{P4}_{\text{placed}}$ − net return P0). A quadratic regression of DIFF on MEAN was performed to assess whether superiority of a treatment depended on soil fertility. Since a preliminary analysis revealed no year effects (results not shown), data from control and NPK plots of both years were pooled. Assuming normally distributed errors around the regression line, the risk that net return $\text{P4}_{\text{placed}}$ < net return P0 (RISK) was computed for each value of MEAN. The RISK was plotted against the MEAN, with 95% confidence limits computed as described by Piepho (2000c).

3. Results

3.1. Multi-factorial experiment

3.1.1. Legumes

Neither N nor P significantly affected legume TDM development over time at any site (Table 2). At some sites cowpea TDM tended to decline consistently over the duration of the experiment, however, none of the regression slopes was significantly different from zero. After 4 years and averaged across both N levels, trend lines predicted a 28% greater groundnut TDM for SSP13 compared to the control (P0) at Fada and a 72% increase at both Koukombo and Kaboli. At the two Guinean sites similar increases in groundnut TDM were predicted for TRockP39 + $\text{P4}_{\text{placed}}$ (data not shown).

3.1.2. Cereals

3.1.2.1. Treatment effects on time trends. In contrast to Sadoré, Gaya and Fada where millet TDM time trends under both cropping systems were unaffected by P and N application, N significantly increased millet TDM trends at Banizoumbou and Goberi (Table 2). Nitrogen effects were even more prominent for maize at the two Guinean sites where large interactions between N and cropping system were observed. In contrast, P effects on time trends in cereal TDM were detectable only at the Sahelian sites of Banizoumbou, Kara Bedji and Goberi and were negligible at any of the sites in the Sudano–Guinean zone. Phosphorus effects appeared to be independent of cropping system. Cropping system effects on cereal TDM were highly significant for all rotations with groundnut but there were no cropping system effects for cowpea (Table 2).

3.1.2.2. Phosphorus application in the Sahelian zone. Compared to the control, $\text{P4}_{\text{placed}}$ was remarkably effective in shifting trend lines upward at two out of three trial sites. At Banizoumbou, the driest site of the experiment, the expression of P effects appeared to be largely governed by N (Fig. 1A and B). Millet TDM in plots that received no P but N, tended to increase over time (Fig. 1B). After 4 years TRockP39 +$\text{P4}_{\text{placed}}$ yielded significantly greater than the unfertilised control independent of N application. Nitrogen application led to final average increases in the predicted millet biomass by 1410 kg ha^{-1} across P levels.

At Sadoré, millet TDM without P strongly declined over time at both levels of N and cropping system. This decline was weaker, though not reversed, with either of the four similarly effective P application strategies tested at this site (Fig. 2). At Kara Bedji, control yield remained constant over time. TRockP39 was the least effective at this site, whereas $\text{P4}_{\text{placed}}$ alone led to predicted TDM increases by 81% and in combination with TRockP39 or TRockP130 by 99 and 133% for the fourth year, respectively (Fig. 3). At Goberi, the relative ranking of P time trends strongly depended on N, which was also reflected in a highly significant N × P interaction (Table 2). Particularly noteworthy was the large increase in the yield enhancing effects of TRockP39 with added N (Fig. 4). Overall, however, N-induced increases in millet TDM were much smaller than these at Banizoumbou (Table 2 and Fig. 1).

3.1.2.3. Phosphorus application in the Sudanian zone. At Gaya, millet TDM levels were overall much lower than at any of the Sahelian sites. Regardless of N or cropping system, slopes of time

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[1] 100 FCFA, the local currency unit = 1 French Franc or about 0.15 US$.

Table 2
P-values for *F*-tests of treatment effects on time trends (slopes) in a multi-factorial experiment conducted over 4 years with nitrogen (N) and phosphorus (P) applied to monoculture legumes and cereals grown in two cropping systems (SYSTEM; monoculture and cereal/legume rotation) at eight sites in West Africa

Site	Precipitation[a]	Treatment factor								
		Legumes[b]			Cereals[c]					
		N	P	N × P	N	P	N × P	SYSTEM	N × SYSTEM	P × SYSTEM
Banizoumbou	510	0.9531	0.0977	0.7367	0.0001	0.0034	0.1968	0.0610	0.5534	0.9556
Sadoré	560	0.3973	0.3468	0.6481	0.7187	0.1129	0.3941	0.1072	0.2238	0.7943
Kara Bedji	590	0.0923	0.6130	0.7368	0.1368	0.0197	0.4501	0.4130	0.7026	0.3203
Goberi	600	0.6199	0.0827	0.1328	0.0501	0.0002	0.0065	0.1287	0.7217	0.4545
Gaya	800	0.9128	0.2824	0.9555	0.4947	0.1714	0.5462	0.3307	0.1621	0.5106
Fada	850	0.4952	0.1835	0.1008	0.4240	0.3315	0.7556	0.0225	0.3537	0.7601
Koukombo	1100	0.1824	0.5973	0.5796	0.0001	0.2398	0.6200	0.0004	0.0003	0.3828
Kaboli	1300	0.5840	0.7230	0.9419	0.0001	0.2485	0.2298	0.0001	0.0001	0.5204

[a] Average annual rainfall for 5–10 years.

[b] Cowpea (*Vigna unguiculata* Walp.) at Banizoumbou, Sadoré, Kara Bedji, Goberi and Gaya; and groundnut (*Arachis hypogaea* L.) at Fada, Koukombo and Kaboli.

[c] Millet (*Pennisetum glaucum* L.) at Banizoumbou, Sadoré, Kara Bedji, Goberi and Gaya; sorghum (*Sorghum bicolor* L. Moench) at Fada; and maize (*Zea mays* L.) at Koukombo and Kaboli.

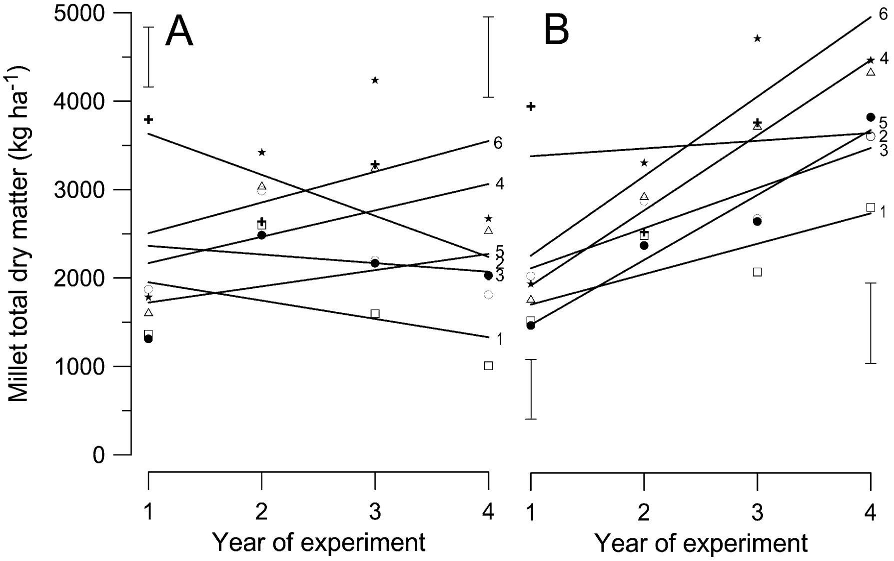

Fig. 1. Millet total dry matter at Banizoumbou, Niger without (A) and with (B) nitrogen (N) at 60 kg N ha^{-1} yr^{-1}. Phosphorus was applied at (1 = □) 0 kg P ha^{-1} (control); (2 = +) annually as SSP at 13 kg P ha^{-1}, (3 = ○) as broadcast 'soft' Tahoua rock phosphate (TRockP) at 39 kg P ha^{-1} once for 3 years; (4 = △) as TRockP at 39 kg P ha^{-1} once every 3 years combined with annually hill-placed SSP or NPK at 4 kg P ha^{-1}; (5 = ●) annually as hill-placed; SSP or NPK at 4 kg P ha^{-1} alone and (6 = ★) as TRockP at 130 kg P ha^{-1} once every 10 years combined with annually hill-placed SSP or NPK at 4 kg P ha^{-1}. The scatter data are least squares means based on yearwise analyses using the same linear mixed model for the description of multi-factorial treatment effects as for the time trend (SLOPE) variable. Trend lines were obtained by connecting predictions in year 1 (P1) and year 4 (P4). Vertical bars show least significant differences ($\text{LSD}_{0.05}$) comparing predicted means for cropping systems in year 1 (P1) and in year 4 (P4), respectively.

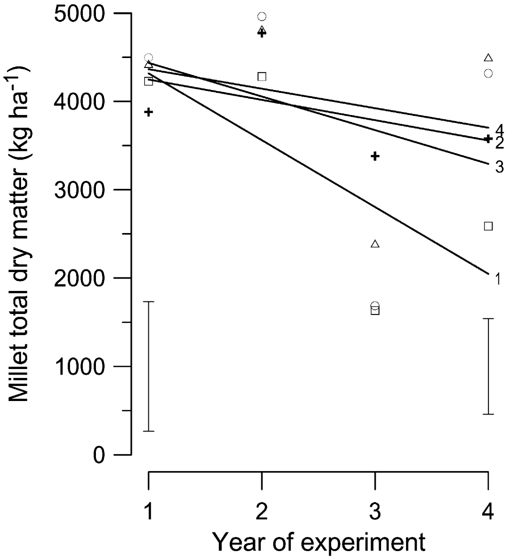

Fig. 2. Millet total dry matter at Sadoré, Niger averaged for nitrogen applied at 0 and 60 kg N ha^{-1} yr^{-1}. For explanation of symbols and numbers see Fig. 1.

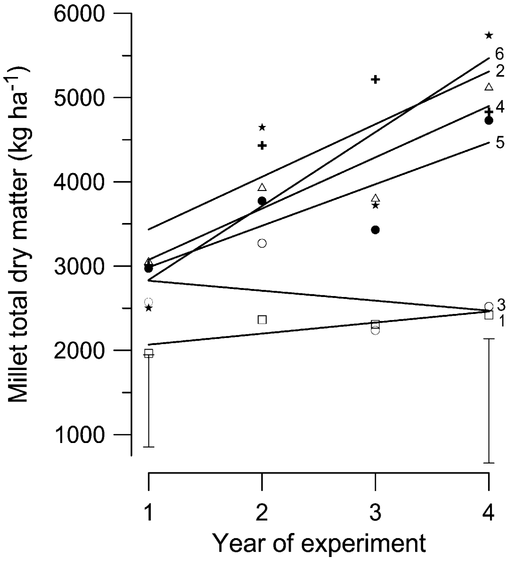

Fig. 3. Millet total dry matter at Kara Bedji, Niger averaged for nitrogen applied at 0 and 60 kg N ha^{-1} yr^{-1}. For explanation of symbols and numbers see Fig. 1.

trends tended to be more negative for higher levels of applied P than for the unfertilised control, (Fig. 5). At Fada, the large rotation-induced increases in sorghum TDM were consistent across all levels of applied N and P. The application of SSP13 and of P4$_{\text{placed}}$ combined with either TRockP39 or TRockP130 led to a millet TDM twice as high as that of the unfertilised control (Fig. 6). For all P treatments,

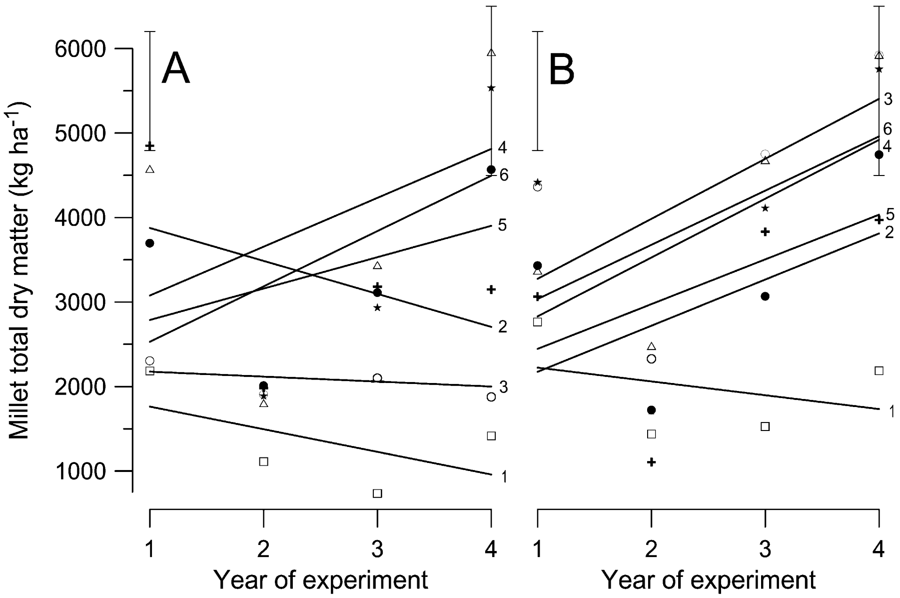

Fig. 4. Millet total dry matter at Goberi, Niger without (A) and with (B) nitrogen at 60 kg N ha^{-1} yr^{-1}. For explanation of symbols and numbers see Fig. 1.

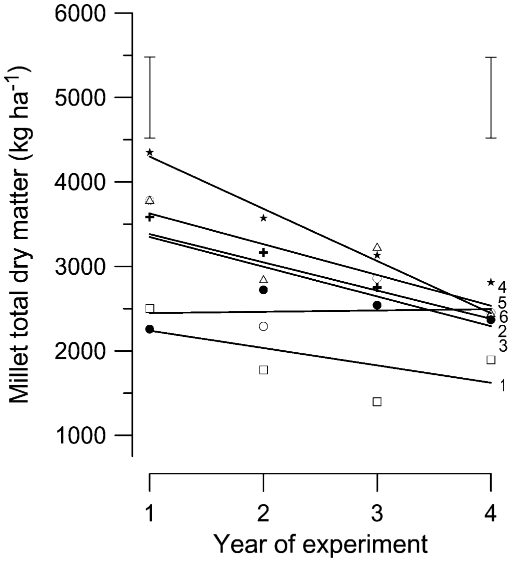

Fig. 5. Millet total dry matter at Gaya, Niger averaged for nitrogen applied at 0 and 60 kg N ha^{-1} yr^{-1}. For explanation of symbols and numbers see Fig. 1.

regression slopes tended to be negative but these slopes were only significant ($P < 0.01$) for the two control treatments without P, continuous SSP13 and TRockP39.

3.1.2.4. Phosphorus application in the Guinean zone. At Koukombo, maize TDM production in continuous control plots remained at a low but constant level throughout the duration of the experiment but increased significantly in rotation plots and with N application. Also, P response strongly depended on N application. In continuous maize plots without N, time trends in the fourth year indicated significant increases in TDM compared to the control only for P placement, TRockP39 and TRockP39 + P4$_{\text{placed}}$ (Fig. 7A). In rotation plots, significant TDM increases compared to the control were noted only for TRockP39 + P4$_{\text{placed}}$ (Fig. 7B). With N application, maize TDM at the end of the experiment was clearly superior for SSP13 and TRockP39 + P4$_{\text{placed}}$, regardless of cropping system (Fig. 7C and D). Initially, P placement alone was overall more effective without N application.

At Kaboli, P effects on maize TDM depended even more strongly on N application than at Koukombo. Trend lines of P treatments did not show any time-related TDM increase without N and none of the slopes was significantly different from the unfertilised control or from zero (Fig. 8A and B). With N application, TDM yield in the control treatment significantly increased over time for rotation but not for continuous maize. In continuous N-fertilised maize, significant

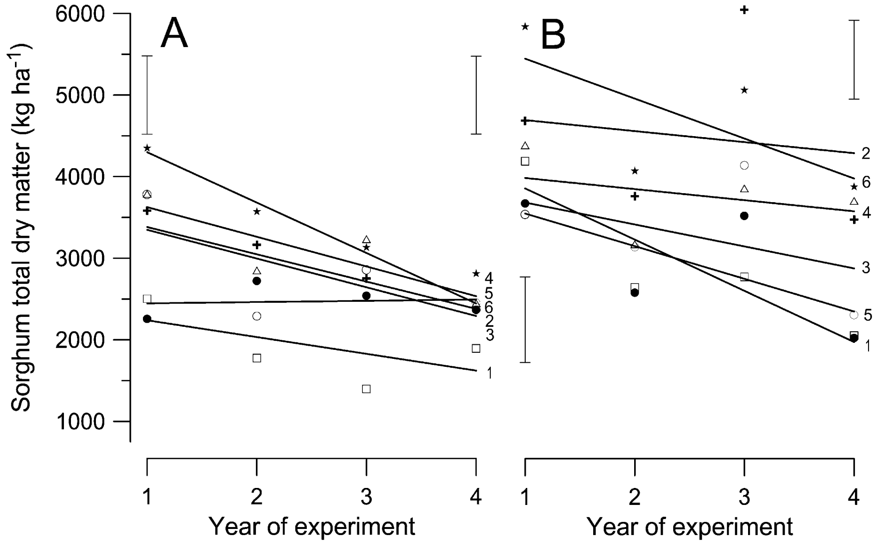

Fig. 6. Total dry matter of continuous sorghum (A) and sorghum after groundnut (B) at Fada, Burkina Faso averaged for nitrogen applied at 0 and 60 kg N ha^{-1} yr^{-1}. For explanation of symbols and numbers see Fig. 1.

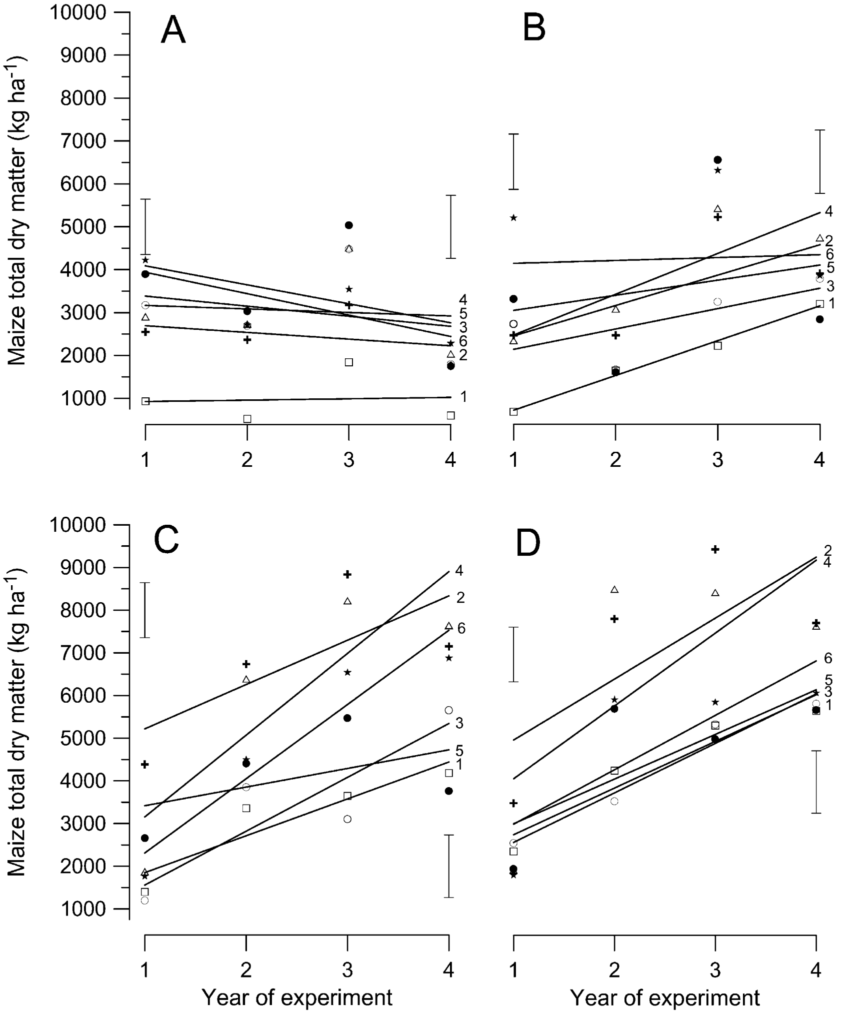

Fig. 7. Total dry matter of continuous maize (A) and maize after groundnut (B) without nitrogen (N) application and continuous maize (C) and maize after groundnut (D) with N at 60 kg ha^{-1} yr^{-1} at Koukombo, Togo. For explanation of symbols and numbers see Fig. 1.

time-depended increases in TDM were noted for P placement in combination with TRockP39 and TRockP130, but P response was much larger and statistically significant for all P treatments in rotation plots with N application (Fig. 8C and D).

3.2. On-farm testing of P placement

In 1998 millet yields in P4$_{\text{placed}}$ plots were, except for two fields, consistently larger than unfertilised control yields, which ranged between 0 and 1030 kg ha^{-1}. The average TDM yield in P4$_{\text{placed}}$ plots was 672 kg ha^{-1}, which was 120% higher than the average in P0 plots. This result was confirmed by the second set of on-farm tests in 1999 which showed average yield increases of 118% for NPK and of 116% for DAP (Fig. 9A and B).

There was a marked response of the difference in net return (DIFF) to the fertility score (MEAN; Fig. 10A). Only for very low productivity scores was the risk of P0 slightly lower than that of P4$_{\text{placed}}$, but in those cases the risks were not significantly different from each other. With increasing soil productivity, P4$_{\text{placed}}$ increasingly outperformed P0. That

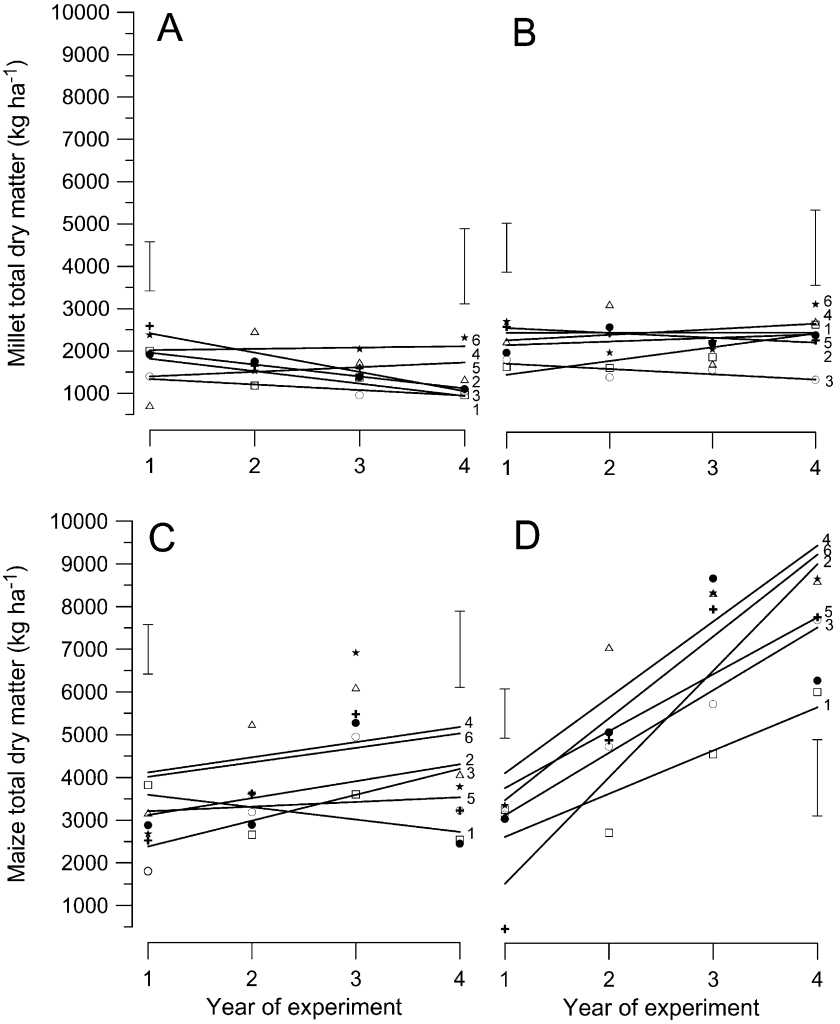

Fig. 8. Total dry matter of continuous maize (A) and maize after groundnut (B) without nitrogen (N) application and continuous maize (C) and maize after groundnut (D) with N at 60 kg ha^{-1} yr^{-1} at Kaboli, Togo. For explanation of symbols and numbers see Fig. 1.

is, for larger MEAN values the probability of P0 to outperform $P4_{placed}$ was significantly lower than 50%.

4. Discussion

4.1. Treatment effects on legumes and legume rotation effects on cereals

While the limited N effects on legume growth in this study may be explained by the overall low yield levels and the legumes' N_2 fixation capacity, the only minor effects of P application on both cowpea and groundnut growth over time were particularly surprising in view of previous findings which showed significant N and P effects for cowpea (Bationo, unpublished data; Bationo and Ntare, 2000) and N effects for groundnut at Sadoré (Hafner et al., 1992). For P application in groundnut, Rebafka et al. (1993b) have shown that on acid sandy Sahelian soils SSP application can be ineffective due to a suppression of molybdenum uptake by sulfate ions in the soil solution. However, this would not explain the lacking response of cowpea to TRockP at Gaya with its low pH and high rainfall.

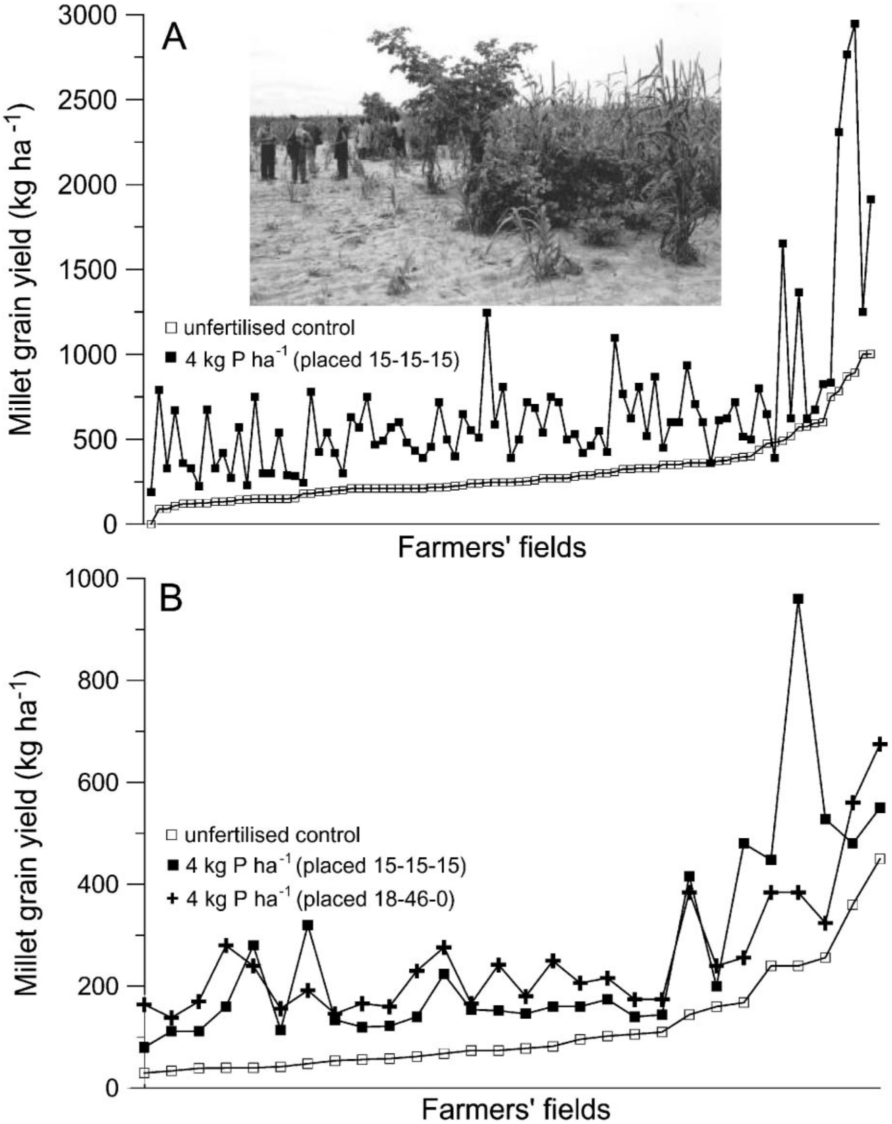

Fig. 9. Effects of hill-placed application of 4 kg P ha^{-1} as NPK (15–15–15) or DAP (18–46–0) at sowing on millet grain yield in farmers' fields in Niger during 1998 (A) and 1999 (B). Yield data were sorted according to their magnitude in unfertilised control plots. The photograph in A shows a farmer's field in Maradi with the unfertilised control plot (left) and a neighbouring plot with P placement to millet (right). Millet grain yield data of 1999 were kindly provided by D. Marchal, FAO, Niamey, Niger.

In this study significant legume rotation effects on cereal TDM time trends were only observed for groundnut which is in contrast to data from Bationo and Ntare (2000) collected over 5 years at three sites in Niger. The reported over 10-fold greater atmospheric N_2 fixation of groundnut compared to cowpea (Peoples and Craswell, 1992) may explain this legume-specific difference in rotation effects assuming that rotation effects on these sites with higher rainfall were caused by improved N availability. Other reasons could be species-dependent changes in pH or ligand exchanging exudates in the rhizosphere soil of legumes which are known to affect P availability (Ae and Otani, 1997; Alvey et al.,

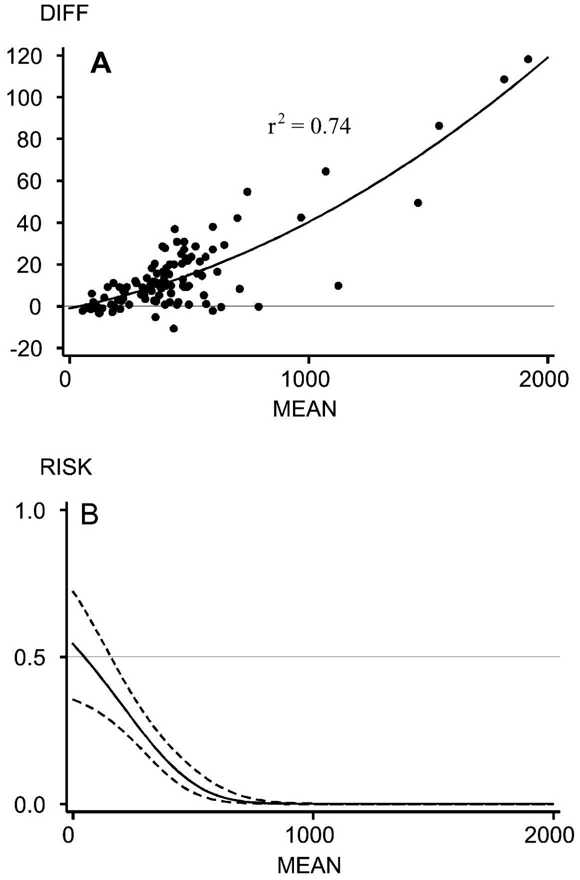

Fig. 10. (A) Quadratic regression between the difference in net returns (DIFF in 1000 FCFA ha^{-1}) for hill-placed application in millet of 4 kg P ha^{-1} ($P4_{\mathrm{placed}}$) as NPK compared to the unfertilised control treatment (P0) and the soil productivity index (MEAN), calculated as $[\frac{1}{2}(P4_{\mathrm{placed}} + P0)]$, for each of the 91 Nigerien farms in 1998. (B) Risk plot depicting the probability that net returns of $P4_{\mathrm{placed}}$ are smaller than those of the unfertilised control treatment P0 as a function of the soil productivity index. Dotted lines indicate the 95% confidence limits.

2001; Bagayoko et al., 2000a; Ohwaki and Hirata, 1992).

4.2. Cereals

4.2.1. Nitrogen versus phosphorus effects

With both cropping systems and regardless of N application, cereal TDM trends without P declined at all Sudano–Sahelian sites except for Banizoumbou and Kara Bedji. This suggests that limited N availability may not be the primary cause for the often observed yield decline in continuous cereal cropping of the drier areas of sub-Saharan West Africa and the subsequent need for extended fallow periods. In the Guinean zone of Koukombo and Kaboli, however, N was clearly the most important growth limiting factor. Phosphorus effects became only significant after N constraints had been removed (Figs. 7 and 8). At a more general level, these results confirm the findings of Poulain et al. (1974) and support the data of Uyovbisere and Lombim (1991), Halm and Dartey (1991), Jallah et al. (1991) and Maduakor (1991). In combination these authors provide consistent evidence that the role of N versus P as primary limiting factors for crop growth increases with rainfall and TDM production from the semi-arid Sahel to the sub-humid Guinean zone of West Africa.

4.2.2. Soluble P versus RockP

Without N, trend lines showed larger cereal TDM production for annual SSP application than for TRockP, regardless of the cropping system, consistently over time and for all sites except for continuous maize at Koukombo. The size of the differences between these two P fertiliser treatments was strongly site-specific. At Kara Bedji, TRockP39 effects were independent of N application and negligible compared to the 116% final TDM increase for SSP (Fig. 3). At Goberi, however, the relative advantage of TRockP39 compared to SSP strongly depended on N application. With the application of 60 kg N ha^{-1}, in the fourth year TRockP39 was twice as effective as SSP in increasing TDM above control without P, whereas without N, SSP was more effective (Fig. 4). The dependence of relative TRockP39 effects on N application is hard to explain but may be related to a more vigorous root growth and thus improved contact between roots and RockP-P in N-fertilised millet. The data also support the results of Bationo et al. (1990) who showed an overall similar effectiveness for TRockP and SSP for this strongly acid site. At Gaya, a site with low pH and comparatively larger rainfall, TRockP and SSP affected millet TDM similarly throughout the duration of the experiment (Fig. 5, Table 1). At Fada, however, a site with similar annual rainfall and clay content to Gaya but with much higher pH, SSP-induced increases in rotation sorghum TDM were twice as large as for TRockP39, irrespective of N application. The similar relative effects of TRockP and SSP observed at the two Guinean sites with their high pH, associated cation exchange capacity and base saturation underline the previously reported predominant importance of soil parameters compared to rainfall in governing P availability from RockP to cereals (Sinaj et al., 2001).

Overall, these results may contribute to ending the decades-old often rather ideological discussion about the advantages and disadvantages of widespread RockP application to counteract P depletion in sub-Saharan West Africa. If P costs are to be carried by farmers and not the general public, cost-effectiveness at the farm-level must be the criterion of choice. The results suggest that locally available high quality RockP can only be an alternative to SSP at the farmers' level if it is much cheaper, properly conditioned to avoid negative farmer reactions to its powdery nature and most of all if its application is restricted to well-defined zones with low pH and high rainfall.

4.2.3. P placement effects on-station and on-farm

Compared to the control, time trends for $P4_{\text{placed}}$ application alone indicated final cereal TDM increases between 50 and 220% across all sites, except for Koukombo and Kaboli, that were rather independent of N and cropping system. At the latter sites the low effectiveness of $P4_{\text{placed}}$ was likely due to the much higher planting densities for maize and the overall higher TDM which caused P application at the NPK rate applied to be only a fraction of total plant P uptake. The fact that the combination of TRockP at 39 and 130 kg P ha^{-1} with $P4_{\text{placed}}$ led to large additive effects across all sites and was rather independent of N and cropping system points to the complementary nature of both forms of P application. While RockP application affects the long-term P status of the soil (Sinaj et al., 2001), the small amount of readily available P in the $P4_{\text{placed}}$ treatment likely stimulated seedling growth and subsequently improved overall P uptake through better developed cereal roots. It was particularly interesting that at the same rate of applied P, grain yield increases with placed mineral fertiliser were similar, irrespective of its type. Placement of NPK contained 9.2 kg N ha^{-1}, of which about half was in the form of ammonium ($NH_4{}^+$), but with DAP, only 3.6 kg N ha^{-1} was applied, however, entirely as $NH_4{}^+$. This indicates that the relatively small but early applied $NH_4{}^+$ component in the NPK fertiliser may have substantially enhanced the P effects on cereal seedlings by directly stimulating root growth (Oikeh et al., 1999; Strasser and Werner, 1995). The choice of whether to apply $P4_{\text{placed}}$ alone or in combination with RockP to enhance the effectiveness of the latter will largely depend on site-specific soil pH conditions and the price of RockP. The on-farm data of this study show that, except for the most marginal soils, $P4_{\text{placed}}$ alone is a yield enhancing strategy of low economic risk (Fig. 10) and may thus help to reverse declining yield trends across a wide range of agro-ecological conditions. However, as a note of caution, it should be mentioned that the 0.9 g N applied together with 0.4 g P in NPK to each planting hill constitutes only between 10 and 20% of a millet plant's total N uptake. At present, it remains unclear what role free-living or rhizosphere-bound N_2-fixing bacteria play within the N balance of the predominantly cereal-based cropping systems of sub-Saharan West Africa and how they are affected by P-induced improved plant growth and likely higher exudation of C-sources in the rhizosphere (Hafner et al., 1993). Therefore, the $P4_{\text{placed}}$-induced large increases in cereal TDM should only be regarded as a first step to a more integrated effort to restore soil fertility and associated social welfare of millions of peasants in this region by targeted inputs of mineral fertilisers and careful prevention of nutrient losses within the predominantly agro-pastoral land-use systems.

Acknowledgements

The authors are grateful to ICRISAT Sahelian Centre (Niger), INERA (Burkina Faso) and IFDC-Africa (Togo) for logistic support, to M. Bagayoko and K. Dossa for their cooperation during data collection and to the Deutsche Forschungsgemeinschaft (DFG) for funding within the SFB308 and an additional grant.

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