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Effects of fertility management strategies on phosphorus bioavailability in four West African soils

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Abstract

Low phosphorus (P) in acid sandy soils of the West African Sudano-Sahelian zone is a major limitation to crop growth. To compare treatment effects on total dry matter (TDM) of crops and plant available P (P-Bray and isotopically exchangeable P), field experiments were carried out for 2 years at four sites where annual rainfall ranged from 560 to 850 mm and topsoil pH varied between 4.2 and 5.6. Main treatments were: (i) crop residue (CR) mulch at 500 and 2000 kg ha^{-1}, (ii) eight different rates and sources of P and (iii) cereal/legume rotations including millet (*Pennisetum glaucum* L.), sorghum [*Sorghum bicolor* (L.) Moench], cowpea (*Vigna unguiculata* Walp.) and groundnut (*Arachis hypogaea* L.). For the two Sahelian sites with large CR-induced differences in TDM, mulching did not modify significantly the soils' buffering capacity for phosphate ions but led to large increases in the intensity factor (C_P) and quantity of directly available soil P (E_{1min}). In the wetter Sudanian zone lacking effects of CR mulching on TDM mirrored a decline of E_{1min} with CR. Broadcast application of soluble single superphosphate (SSP) at 13 kg P ha^{-1} led to large increases in C_P and quantity of E_{1min} at all sites which translated in respective TDM increases. The high agronomic efficiency of SSP placement (4 kg P ha^{-1}) across sites could be explained by consistent increases in the quantity factor which confirms the power of the isotopic exchange method in explaining management effects on crop growth across the region.

Introduction

The large effects of crop residues (CR), applied as surface mulch, on the development of pearl millet (*Pennisetum glaucum* L.) and sorghum [*Sorghum bicolor* (L.) Moench], grown on phosphorus (P) poor, acid, sandy Sahelian soils with clay contents near 50 g kg^{-1} have been well documented. Considerable research, both on-station and on-farm, has been conducted on this subject in the southern Sahelian zone of West Africa, with 300 – 600 mm annual rainfall (Bationo and Mokwunye, 1991; Bationo et al., 1992, 1993). The yield-enhancing effects of CR have been explained by increases in root growth (Hafner et al., 1993b; Kretzschmar et al., 1991) and soil biological activity (Hafner et al., 1993a; Mando and Stroosnijder, 1999), protection of seedlings from the effects of wind erosion, improved water availability and up to 4 °C lower soil surface temperatures at the onset of the growing season (Buerkert et al., 2000). Nevertheless, increases in soil P availability through dust-induced pH increases, anion displacement and chelation of aluminium and iron ions have also been reported (Buerkert and Lamers, 1999; Kretzschmar et al., 1991). However, for the Sudanian zone, with 600 – 900 mm annual rainfall, CR-induced crop growth increases were reported to be smaller than in the Sahelian zone (Bationo et al., 1995). This smaller CR effect on total dry matter (TDM) with increas-

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ing rainfall has been attributed to the lower incidence of erosive sandstorms, lower temperatures and higher clay contents of the soils (Buerkert et al., 2000).

Due to the low P status of most soils in the Sudano-Sahelian zone, the effects of P fertilisation on crop growth are generally larger than those of CR. Significant site-specific differences in the agronomic efficiency among P sources, particularly between local rockphosphates and water soluble P fertilisers were noted. These can be explained by differences in the physico-chemical and mineralogical composition of the phosphate rocks used, soil pH, soil texture, soil exchangeable calcium (Ca) and rainfall (Abekoe and Tiessen, 1998; Sale and Mokwunye, 1993). Whereas finely ground rockphosphate from Parc du W and Tahoua was reported to be 46 and 76% as effective as SSP in increasing millet yield at Goberi in south-western Niger (Bationo et al., 1990), relative rockphosphate effects were significantly lower only 50 km further north (Buerkert and Hiernaux, 1998). The limited data available show that crop growth increases following P application are generally directly related to increases in levels of plant available P (P-Bray). Bationo and Buerkert (2000) reported that 14 years of consecutive residue mulch application at 4 t ha^{-1} $year^{-1}$ led to a decline in the maximum P sorption, as calculated using Langmuir isotherms, from 91 mg P kg^{-1} for unmulched control plots without mineral P application to 54 mg P kg^{-1} with P fertiliser, whereas the additional application of CR mulch decreased maximum P sorption to 37 mg P kg^{-1}.

Mechanisms, such as P mobilisation, possibly underlying the yield increasing effects of cowpea (*Vigna unguiculata* L. Walp) and groundnut (*Arachis hypogaea* L.) grown in rotation with either of the two cereals in Sudano-Sahelian West Africa are poorly understood. Recent data indicate that an early increase of mineral nitrogen (N) in plots sown to cereals after legumes compared with continuous cereal plots and an earlier infection of cereal roots with native arbuscular mycorrhizae (AM) may be more important in explaining rotation effects for subsequent cereals than a legume-induced increase in P availability (Bagayoko et al., 2000). This, however, needs to be verified by further studies.

Due to the overriding importance of P for plant growth in the soils of the Sudano-Sahelian region, a better understanding of the effects of CR, cereal/legume rotation and P application (particularly of local rockphosphates) on plant growth and on P availability and dynamics is required. A mechanistic understanding of the P dynamics in the predominant poorly buffered soils is necessary to (i) predict the effects of the soil fertility management strategies on the sustainability of agricultural systems and (ii) draw broader conclusions from site-specific results. The main objective of the present study was to examine whether the use of the isotopic exchange kinetics technique for phosphate ions (Fardeau, 1996) could help to a better understanding of the effects of agricultural practices such as CR mulching, cereal/legume rotations and P fertiliser application on plant available P and thus contribute to explain effects on crop growth and yield increases. As field replicates were available for each sample, the data also allowed an assessment of the spatial variation in P dynamics.

Materials and methods

Field experiments

Experimental design

The four experimental sites selected for the present study were part of a large factorial crop rotation experiment arranged in a split-plot design with two replications. The experiment was conducted under rainfed conditions from 1995 to 1999 in the Sahelian, Sudanian and Guinean zones of sub-Saharan West Africa (Bagayoko et al., 2000; Buerkert et al., 2000). The soils were Psammentic Paleustalfs at Kara Bedji (13°15′N, 2°32′E) and Goberi (12°58′N, 2°50′E) in the southern Sahelian zone and an Arenic Kandiustalf at Gaya-Bengou (11°59′N, 3°32′E) in the Sudanian zone of Niger and a Haplustalf at Fada-Kouaré (11°59′N, 0°19′E) in the Sudanian zone of Burkina Faso. With their range of soil chemical properties they are typical for this region (Table 1).

The factorially combined mainplot factors of relevance for this study were (i) P broadcast annually as SSP at 0 kg P ha^{-1} (control) and 13 kg P ha^{-1} (SSP13), as ‘soft’ Tahoua rockphosphate at 39 kg P ha^{-1} (TRP39) once in 1995 for 3 years and as ‘hard’ Kodjari rockphosphate at a 10-yearly rate of 130 kg P ha^{-1} (KRP130), a treatment carried out to test the impact of a heavy one-time P application to severely P deficient soils and (ii) cereal crop residues (CR) applied as surface mulch at 500 kg DM ha^{-1} (CR500, corresponding to farmers’ current practice) and 2000 kg DM ha^{-1} (CR2000). In addition to these six treatments, one additional treatment at CR500 was used: annual SSP placement with the seed at a rate of 4 kg

Table 1. Mean annual precipitation and initial soil chemical parameters for four sites in West Africa at 0 – 0.1 and 0.1 – 0.2 m depth in May 1995

Site	Depth (m)	Precipitation[a] (mm)	pH[b]	Organic C (g kg^{-1})	P-total (mg kg^{-1})	P-Bray	CEC$_e$[c] (cmol$_c$ kg^{-1})	BS[d] (%)	Clay	Fe-dithionite (g kg^{-1})
Kara Bedji	0 – 0.1	590	4.2	1.7	43.8	2.1	0.7	65	40	1.9
	0.1 – 0.2		4.1	1.4	48.3	1.6	0.8	46	n.d.[e]	2.2
Goberi	0 – 0.1	600	4.2	1.9	38.8	2.5	0.8	60	30	4.5
	0.1 – 0.2		4.1	1.2	38.6	0.9	0.9	40	n.d.	4.7
Gaya	0 – 0.1	800	4.5	3.7	129.5	4.1	1.1	83	130	22.0
	0.1 – 0.2		4.0	3.0	156.5	1.0	1.6	50	n.d.	27.8
Fada	0 – 0.1	850	5.6	5.9	60.8	1.6	3.2	100	150	4.3
	0.1 – 0.2		5.1	4.5	47.8	1.0	2.3	98	n.d.	4.9

[a]Average annual rainfall of 5–10 years.
[b]pH in 0.01 *M* KCl (1:2.5).
[c]Effective cation exchange capacity.
[d]Base saturation.
[e]No separate data for each depth available.

P ha^{-1} (SSP4). Tahoua and Kodjari are names of local mining sites for rockphosphates in Niger and Burkina Faso, respectively.

Crop residues were applied as mulch to the soil surface of the corresponding plots in the middle of the dry season (from November to May) and uniformly redistributed before planting. Single superphosphate was broadcast annually and rockphosphates once in early May at the beginning of the rainy season to the respective plots. Anually calcium ammonium nitrate at 30 kg N ha^{-1} was applied to all plots in three applications, 25% at 10 days after sowing, 25% at thinning and 50% at booting. Mainplot size was 10 × 10 m and subplot size 5 × 5 m. At the mainplot level the design allowed the estimation of cropping system effects with 16 replicates, of CR effects with twelve replicates and of P effects with eight replicates.

Landrace millet and cowpea were the crops sown in Niger, whereas sorghum and groundnut were sown in Burkina Faso. All mainplot treatments were split into four subplots, which contained the cropping systems: continuous cereal, continuous legume and both phases of the cereal/legume rotation. To examine cropping systems effects on P bioavailability, for this study only continuous cereal plots and plots with legumes after cereals were selected. In millet/cowpea cropping systems, millet was planted with the first major rain at the end of May or early June, 15 days before cowpea was sown. For sorghum/groundnut cropping systems, both crops were planted simultaneously in June of each year as described by Bagayoko et al. (2000).

Plant and soil sampling

In May 1997, before the third cropping cycle, five subsamples of the topsoil at 0 – 0.1 and 0.1 – 0.2 m depth were taken in each plot, bulked, air-dried and sieved. Sampling was performed with an aluminium tube in the centre of two crop rows. To compare treatment effects with the original soil status, similar samples were taken in four fallow areas immediately adjacent to the experiment. After the 1997 growing period, TDM yields were determined from the three central rows of each subplot without border plants at both ends of each row. Corresponding grain yields which were also determined were not reported in this study but in Bagayoko et al. (2000). Total dry matter rather than grain yields were chosen here because they better reflected total P uptake and were less affected by rainfall distribution, pests and diseases.

Soil analyses

Total soil P was determined colourimetrically following soil digestion in hot 11.6 *M* $HClO_4$ (John, 1970). With the same colourimetric method also orthophosphate concentration in the soil solution was determined. Organic C was measured according to Walkley and Black (1934) and iron (Fe) oxide concentration was determined using atomic-absorption spectrometry following dithionite-citrate-bicarbonate extraction (Mehra and Jackson, 1960).

Available soil phosphorus

According to White and Beckett (1964), P availability is governed by three factors: (i) *the intensity factor*, which is the activity of phosphate ions ($H_2PO_4^-$; HPO_4^{2-}) in the soil solution; (ii) *the quantity factor*, which is the amount of phosphate ions that can be released into the soil solution from the solid phase of the soil during the interval of time considered for plant growth and (iii) *the buffer capacity*, which describes the ability of a soil to maintain the intensity factor constant when the quantity varies.

In routine analysis, P availability in soils is generally described by the quantity factor alone. Chemical extractions might extract variable proportions of available and unavailable forms of P depending on the extracting agent and its concentration, on pH, on shaking time and on soil properties (Kato et al., 1995). Results from isotopic exchange kinetics experiments showed that (i) the P buffering capacity of the soils was strongly correlated with the Fe and aluminium (Al) oxide content and therefore could be predicted from a soil's parent material (Frossard et al., 1993; Sinaj et al., 1992) and (ii) the quantity of isotopically exchangeable P measured after 1 minute (E_{1min}), which is the immediately plant available P, was affected by soil parameters and management.

Routine analysis

The P-Bray extraction method (P-Bray 1; Olsen and Sommers, 1982) has been reported previously as appropriate to estimate plant available P for acid sandy soils of the Sudano-Sahelian zone with a low P fixation capacity and was therefore used as a reference (Bationo et al., 1991).

Isotopic exchange kinetic and E value calculation

The experimental procedures for isotopically exchangeable phosphorus, conducted on a soil–solution system in a steady-state with a soil:solution ratio of 1:10 have been recently described (Frossard and Sinaj, 1997). After the addition of carrier free ^{33}P-labeled phosphate ions to a soil–solution system in steady state, three parameters were determined: (i) C_P, the concentration of water soluble P (mg P l^{-1}), (ii) R/r_1, the ratio of total introduced radioactivity (R) to the radioactivity remaining in solution after 1 min of isotopic exchange (r_1) and (iii) n, a parameter providing an estimate of the decrease of the radioactivity $r(t)$ in soil solution with time t.

The quantity, $E(t)$ (mg P kg^{-1} soil) of isotopically exchangeable P at time t was calculated from Eq. (1), assuming that (i) ^{31}P and ^{33}P had the same fate in the system and (ii) that at a given time t, the specific activity of the P in the soil solution was identical to that of the soil's isotopically exchangeable P.

$$E(t) = 10C_P \times R/r(t), \quad (1)$$

where the factor 10 arises from the soil:solution ratio of 1 g of soil in 10 ml of water so that 10 C_P is equivalent to the water soluble P content of the soil expressed in mg kg^{-1}.

R/r_1 is an estimation of the P ion buffering capacity of soils (Frossard et al., 1993; Tran et al., 1988). With R/r_1 being higher than 5, the buffering capacity is considered to be high, with 2.5 – 5 medium and below 2.5 low.

To obtain data that are relevant from physiological and agronomic points of view Barber (1995) and Fardeau (1996) proposed the following pools depicting P availability:

(i) the pool of free phosphate ions (P_F): Ions present in this pool are composed of ions in the soil solution and those ions that are adsorbed on the solid phase of the soil but have the same kinetic properties than those in solution (Fardeau et al., 1985). Phosphate ions located in this compartment are completely and immediately plant available.

(ii) the pool of P exchangeable between 1 min and 1 day ($E_{1min-1d}$) corresponds to the quantity of P exchangeable during a period equivalent to the time of active P uptake by a single root or by a root hair.

(iii) the pool of P exchangeable between 1 day and 3 months (E_{1d-3m}) corresponds to the quantity of phosphate exchangeable during a period equivalent to the time of active P uptake by the entire root system of an annual crop.

(iv) the pool of P which can not be exchanged within 3 months ($E_{>3m}$).

The P content of the pool of free ions (P_F) can be approximated in low P fixing soils such as from the four sites used in this study by E_{1min} (Tran et al., 1988). The P content of $E_{1min--1d}$ and E_{1d--3m} pools is calculated using equation [1]. The P content of $E_{>3m}$ is calculated as the difference between the total P and the amount of P exchangeable within 3 months ($E_{>3m}$).

Finally, such a method provides information on: (i) the P concentration in the soil solution (C_p) which corresponds to the intensity factor, (ii) the P content of the pool of free ions (P_F) and the quantity of isotopically exchangeable P [$E(t)$] which give information on the quantity factor and (iii) the $R/r(1)$ ratio which corresponds to the capacity factor.

Table 2. Total of dry matter yield (kg ha^{-1}) at harvest for millet and sorghum as affected by phosphorus (P) application at 0 (control), 4 (SSP4), 13 (SSP13), 39 (TRP39) and 130 (TR130) kg P ha^{-1}, by crop residues applied as mulch (CR) at 500 and 2000 kg ha^{-1} and by cropping system (continuous cereal and cereal/legume rotation) in the Sahelian zone of Niger at Kara Bedji and Goberi and in the Sudanian zone of Niger (Gaya) and Burkina Faso (Fada)

Sahelian zone	Kara Bedji				Goberi			
P-level[a]	Continuous		Rotation		Continuous		Rotation	
	CR500	CR2000	CR500	CR2000	CR500	CR2000	CR500	CR2000
	(kg ha^{-1})							
Control	2500	4060	1170	4000	1730	2840	2140	3130
SSP4	2750	n.d.[b]	4170	n.d.	2200	n.d.	4020	n.d.
SSP13	1870	4920	3420	4830	2790	4600	3970	5310
TRP39	4450	3860	4200	4220	2700	3630	4570	4300
KRP130	3500	n.d.	2580	n.d.	2510	n.d.	3810	n.d.
	F-probabilities[c]							
System	0.954				0.011			
CR	0.103				0.020			
P	0.410				0.031			
CR × P	0.333				0.227			
Sudanian zone	**Gaya**				**Fada**			
P-level[a]	Continuous		Rotation		Continuous		Rotation	
	CR500	CR2000	CR500	CR2000	CR500	CR2000	CR500	CR2000
	(kg ha^{-1})							
Control	1140	2070	1490	2060	3290	2710	3870	4340
SSP4	2850	n.d.	3290	n.d.	3780	n.d.	4090	n.d.
SSP13	4290	2110	3270	3530	5920	7170	6450	7020
TRP39	2120	2000	2660	2230	6090	3660	5240	5650
KRP130	2890	n.d.	4010	n.d.	4240	n.d.	5750	n.d.
	F-probabilities[c]							
System	0.357				0.135			
CR	0.710				0.953			
P	0.056				0.069			
CR × P	0.309				0.677			

[a] SSP, single superphosphate; TRP, 'soft' Tahoua rockphosphate; KRP, 'hard' Kodjari rockphosphate.
[b] No data available.
[c] *F*-values refer only to the factorially combined treatments.

Statistical analysis

Variances for all soil and crop data were analysed with GENSTAT (Lawes Agricultural Trust, 1993). Depth intervals were treated as split-plots thereby taking into account their spatial dependence.

Results

Plant dry matter

In the Sudanian zone average TDM yields for the third cropping season (1997) reached almost 5 t ha^{-1} for sorghum at Fada but only 2.6 t ha^{-1} for millet at Gaya. At the two Sahelian sites millet TDM amounted to about 3.5 t ha^{-1} (Table 2). Across all other treatments, mulch-induced increases in cereal TDM were 47% at Kara Bedji and 33% at Goberi in the Sahelian zone, whereas they were negligible at the two Su-

Table 3. P-Bray values at the onset of the rainy season 1997 in the topsoil (0 – 0.1 m depth) of Kara Bedji and Goberi (Sahelian zone) and Gaya and Fada (Sudanian zone). Effects of phosphorus applications at 0 (control), 4 (SSP4), 13 (SSP13), 39 (TRP39) and 130 (KRP130) kg P ha^{-1} and crop residues (CR) at 500 and 2000 kg ha^{-1}

P-level	Sahelian zone				Sudanian zone			
	Kara Bedji		Goberi		Gaya		Fada	
	CR500	CR2000	CR500	CR2000	CR500	CR2000	CR500	CR2000
	(mg kg^{-1})							
Control	2.6	4.4	2.5	2.5	3.2	3.5	2.4	2.2
SSP4	3.4	n.d.[b]	6.6	n.d.	4.3	n.d.	2.7	n.d.
SSP13	6.2	7.0	4.3	4.1	5.1	4.7	6.0	3.1
TRP39	7.1	9.5	10.3	7.5	4.3	6.1	2.9	2.4
KRP130	7.1	n.d.	14.5	n.d.	7.0	n.d.	2.8	n.d.
	F-probability[c]							
Site	< 0.001							
System	0.707							
P	< 0.001							
CR	0.993							
Site × P	< 0.001							
Site × CR	0.002							

[a]SSP, single superphosphate; TRP, 'soft' Tahoua rockphosphate; KRP, 'hard' Kodjari rockphosphate.
[b]No data available.
[c]*F*-values refer only to the factorially combined treatments.

danian sites. Compared with continuous cereal plots, cereal yields in legume rotation treatments were 36% higher at Goberi and about 15% higher at Gaya and Fada. No rotation effect was observed at Kara Bedji.

Compared with plots without P, cereal TDM increases in plots fertilised annually with 13 kg P ha^{-1} amounted to 95% at Gaya, 87% at Fada, 69% at Goberi and 28% at Kara Bedji. The application of Tahoua rockphosphate at a 3-yearly rate of 39 kg P ha^{-1} appeared, across CR levels and cropping systems, most effective at Fada and Goberi. The 10-yearly rate of Kodjari rockphosphate (KRP) with CR at 500 kg ha^{-1}, however, increased cereal TDM by 162% at Gaya, 66% at Kara Bedji and Goberi and by 63% at Fada compared with the unfertilised control. Placement of 4 kg P ha^{-1} with the seed led to large cereal TDM increases at all sites, except at Fada.

P-Bray

Averaged across P and CR treatments, the lowest P-Bray values for all sites were observed at Fada and the highest at Kara Bedji. Irrespective of the P level, CR2000 led to an average increase of 32% in P-Bray at Kara Bedji and of 14% at Gaya compared with CR500 (Table 3). After 2 years, P-Bray increases with repeated application of SSP13 were largest at Kara Bedji and with TRP39 at Goberi, smallest increases with TRP39 were measured at Fada. Compared with the unfertilised control, the 10-yearly rate of rockphosphate (KRP130) with CR500 increased P-Bray over 5-fold at Goberi, over 2-fold at Kara Bedji and Gaya but had no effect at Fada.

Isotopically exchangeable P

Cropping systems

The combined analysis of variance across sites, and subsequent separate data analyses at each site, showed that the quantities of isotopically exchangeable P were not significantly different between continuous and rotation treatments. Therefore, data for both cropping systems were pooled for each depth leading to four replicates for each reported measurement. The data presented in Figs. 1 – 4 refer to the upper soil layer (0 – 0.1 m) while treatment effects were generally similar but less pronounced at 0.1 – 0.2 m depth.

Crop residues

At Gaya the P buffering capacity, as defined by R/r_1, was over 3-fold higher than at Goberi and 5-fold higher than at Kara Bedji and Fada (Figs. 1 – 4). Compared with treatment CR500, treatment CR2000

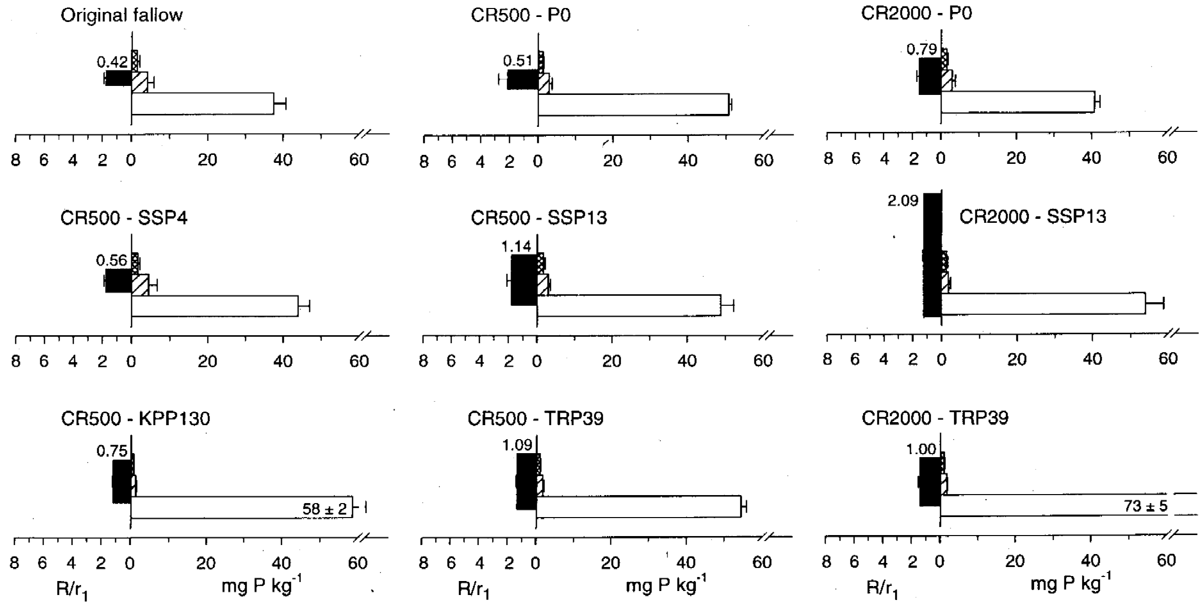

Figure 1. Kara Bedji (Sahelian zone of Niger). The different P pools at 0–0.1 m depth are schematised with rectangles. For the pool E_{1min} (single bar to the left in each graph): (i) the height of rectangle is proportional to the concentration (C_P) of phosphate ions in the soil solution and represents the 'intensity factor', (ii) the surface of this rectangle is proportional to the amount of P isotopically exchangeable within 1 min (E_{1min}), (iii) the length of this pool is proportional to the ratio, R/r_1, and represents a good indicator of the 'capacity factor'. The three P pools $E_{1min-1d}$, E_{1d-3m} and $E_{>3m}$ (bars to the right in each graph from top to bottom) are represented with a uniform height and their length is proportional to their P content. Wherever visible the small bar at the end of each pool represents one standard error of the mean.

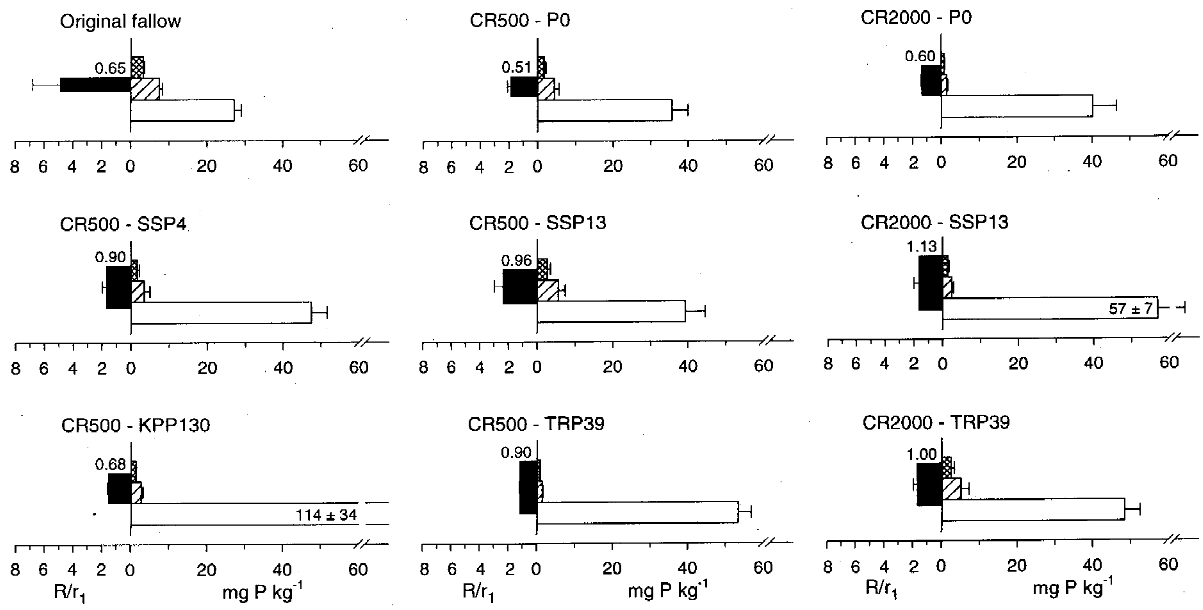

Figure 2. Goberi (Sahelian zone of Niger). Representation of different P pools at 0–0.1 m depth as in Figure 1.

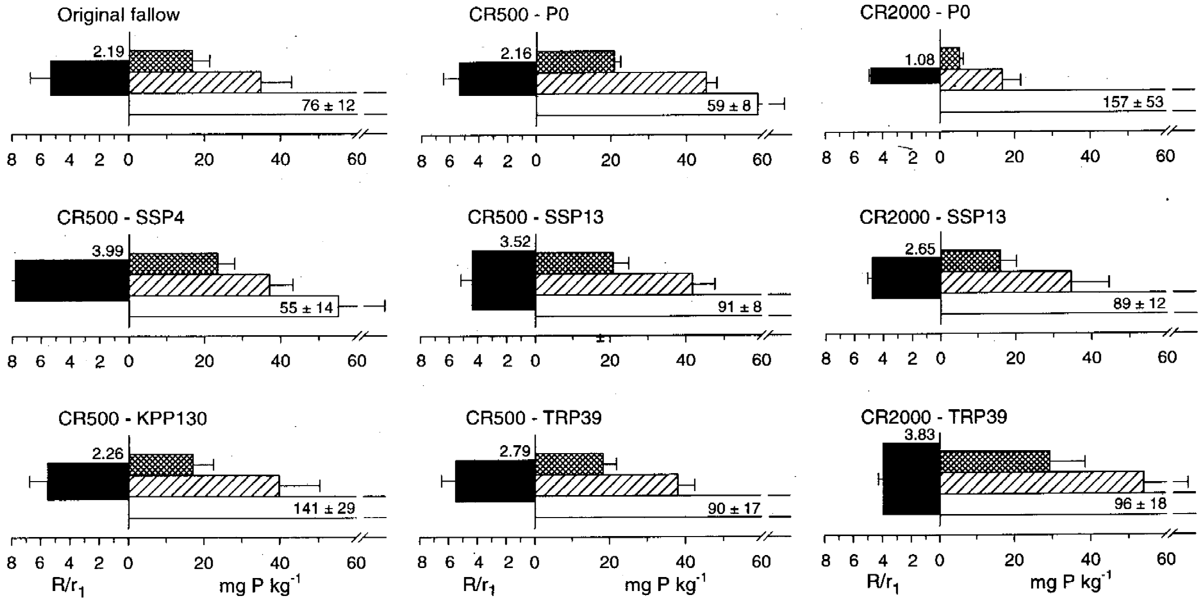

Figure 3. Gaya (Sudanian zone of Niger). Representation of different P pools at 0–0.1 m depth as in Figure 1.

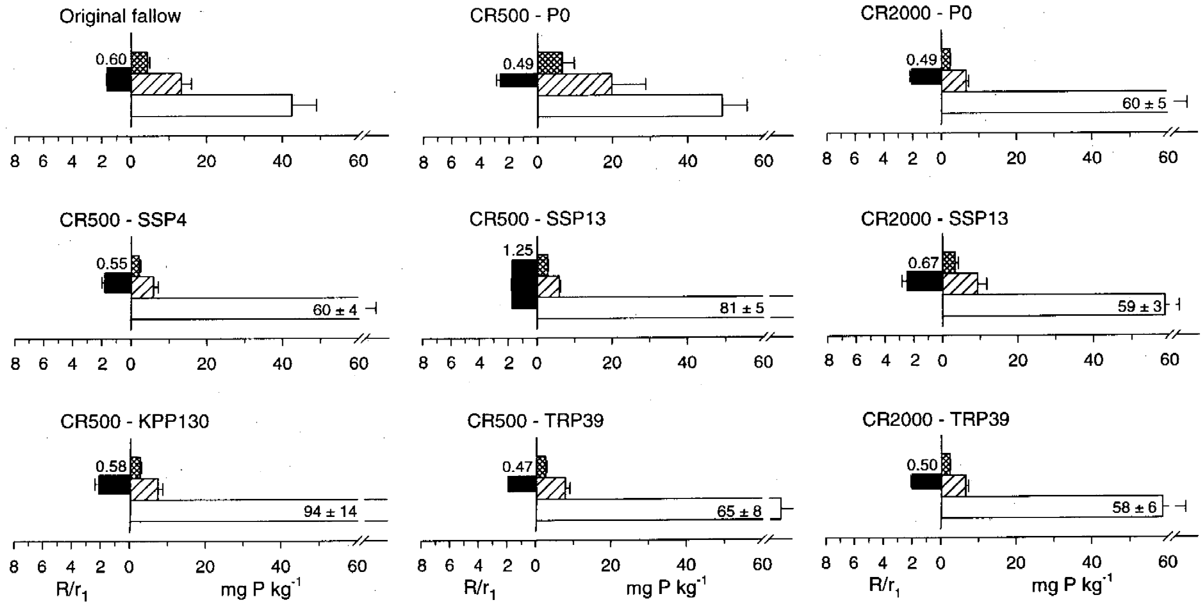

Figure 4. Fada (Sudanian zone of Burkina Faso). Representation of different P pools at 0–0.1 m depth as in Figure 1.

tended to decrease the R/r_1 values for PO and SSP13 at Kara Bedji, Goberi and Gaya in both soil layers but did not have any effect at Fada. In the upper soil layer, increasing CR application also led to a highly significant site × CR interaction for the intensity factor (C_P; P = 0.006). While CR2000 increased the intensity factor from 48 to 78 μg P l^{-1} at Kara Bedji and from 40 to 48 μg P l^{-1} at Goberi, a decrease from 29 to 20 μg P l^{-1} was observed at Fada. No CR effects on the intensity factor were noted at Gaya. Also CR2000 led to an increase in the isotopically exchangeable P within 1 min (E_{1min}) by 42% at Kara Bedji and by 15% at Goberi, whereas respective decreases of 12 and 33% occurred at Gaya and Fada. Similar site-specific differences of CR effects were noticed for total P but not

Table 4. F-probabilities for the concentration (C_P; μgP l^{-1}) of P ions in the soil solution, the buffering capacity (R/r_1), the rate of disappearance of the tracer from the solution after 1 min (n) and the quantity of isotopically exchangeable P in the soil after 1 min (E_{1min}; mg P kg^{-1}) at four sites in West Africa. Effects of cropping system (continuous cereal and cereal/legume rotation), phosphorus (P) application, crop residues (CR) application and soil depth

Factor	Kara Bedji				Goberi			
	C_P	R/r_1	n	E_{1min}	C_P	R/r_1	n	E_{1min}
System	0.783	0.641	0.246	0.950	0.583	0.672	0.530	0.450
P	<0.001	0.397	0.101	0.003	0.018	0.338	0.334	<0.001
CR	0.004	0.424	0.076	0.066	0.255	0.733	0.557	0.003
P × CR	0.002	0.145	0.035	0.054	0.226	0.228	0.144	0.410
Depth	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Depth × P	0.003	0.559	0.156	0.002	0.004	0.357	0.358	0.015
Depth × CR	0.033	0.883	0.880	0.036	0.215	0.861	0.276	0.890
Depth × P × CR	0.080	0.276	0.448	0.159	0.043	0.236	0.179	0.178
CV (%)	44	44	26	30	26	86	22	19

	Gaya				Fada			
	C_P	R/r_1	n	E_{1min}	C_P	R/r_1	n	E_{1min}
System	0.451	0.342	0.239	0.206	0.183	0.212	0.128	0.839
P	0.009	0.199	0.575	0.041	<0.001	0.480	0.033	<0.001
CR	0.771	0.014	0.473	0.957	0.034	0.644	0.708	0.214
P × CR	0.040	0.403	0.833	0.124	<0.001	0.294	0.020	0.022
Depth	<0.001	<0.001	0.595	<0.001	<0.001	0.024	0.040	0.002
Depth × P	0.006	0.069	0.691	0.046	0.003	0.933	0.537	0.003
Depth × CR	0.399	0.009	0.075	0.062	0.023	0.862	0.763	0.015
Depth × P × CR	0.042	0.355	0.202	0.999	0.016	0.769	0.316	0.026
CV (%)	35	29	54	23	37	26	22	27

for the P pools of $E_{1min-1d}$, E_{1d-3m} and $E_{>3m}$ (Figs. 1–4; Table 4).

Phosphorus application

Across CR levels, the two applications of SSP at 13 kg ha^{-1} led to a doubling of the intensity factor C_P in the upper soil layer at Goberi, Gaya and Fada (Fig. 2–4), whereas the intensity was tripled at Kara Bedji (Fig. 1; $P < 0.001$). In contrast, the 39 kg P ha^{-1} applied as soft rockphosphate (TRP39) in 1995 did not affect C_P values at Fada but led to increases from 31 to 59 μg P l^{-1} at Kara Bedji, from 28 to 54 μg P l^{-1} at Goberi and from 28 to 64 μg P l^{-1} at Gaya. Compared with the 3-yearly rate of 'soft' Tahoua rockphosphate (TRP39), the 10-yearly rate of 'hard' Kodjari rockphosphate (KRP130) at CR500 had much lower effects on C_P values at all sites, except at Kara Bedji where it increased from 22 to 49 μg P l^{-1}. The placement of SSP only increased C_P at Kara Bedji (+60%) and Goberi (+123%). At the onset of the 1997 growing season, the isotopically exchangeable P within 1 min (E_{1min}) was twice as high in plots with annual SSP application at 13 kg P ha^{-1} than in unfertilised control plots across all sites and CR treatments. The application of TRP39 led to an increase of the E_{1min} value by 60% at Kara Bedji, 71% at Goberi and 105% at Gaya ($P < 0.001$), but did not affect E_{1min} at Fada. For KRP130 across sites, E_{1min} values were similar to those of unfertilised control plots. At Fada and Kara Bedji the pools of $E_{1min-1d}$ and E_{1d-3m} tended to be reduced with either form or amount of P application but they were increased with SSP13 and TRP39 at Goberi and particularly at Gaya (Figs. 1 – 4). For $E_{>3m}$, the least available P pool, large increases were observed with SSP13 and particularly with TRP39 and KRP130 at all sites, except at Kara Bedji.

Discussion

Soil P status

Total P in the soils of this study was about 10 times lower than commonly observed in soils of temperate zones. The very low P fixing capacity for phosphate ions in the soils (Figs. 1–4) is directly related to the low levels of dithionithe-extractable Fe (Table 1). Thus P application as water soluble P could lead to significant increases of the intensity and the quantity factor. There was no correlation between E_{1min} or E_{1min} plus $E_{1min-1d}$ and P-Bray ($r < 0.15$). This means that the P-Bray 1 method does not well reflect the P quantity factor in these soils.

Effects of surface mulching

Crop residues at 2000 kg ha^{-1} led to large increases in the easily available P fraction at Kara Bedji and Goberi, the two Sahelian sites, as evidenced by the large increases in the quantity (E_{1min}) and intensity (C_P) factors compared with the low CR application rate Fig. 1–2. On these highly P deficient sandy soils the mulching effect on soil P availability may partly explain the observed CR effect on TDM. Average P contents in mulched cereal stover were 0.32 kg P t^{-1} at Kara Bedji and Goberi, 0.71 kg P t^{-1} at Gaya and 0.49 kg P t^{-1} at Fada. A total decomposition of crop residues within 12 months was only observed at Fada, the more humid Sudanian site. Annual recycling of P from mineralisation of CR therefore would have only made a minor contribution to available P even if complete decomposition of CR was assumed. The significant increase in P availability did not result from any significant CR-induced decrease in the soils buffering capacity (Figs. 1 and 2; Table 4). The apparent stability of the capacity factor, despite an increase in the quantity factor, could be explained by the slight increase in the pH of the surface soil resulting from dust deposition (Buerkert et al., 2000; Stahr and Herrmann, 1996). The dust-related increases in pH by 0.2 units at Kara Bedji and Goberi, however, led to respective decreases in exchangeable Al^{3+} from 0.16 to 0.10 cmol$_c$ kg^{-1} and 0.10 to 0.06 cmol$_c$ kg^{-1}. This reduction in strong phosphate binding sites combined with a likely increase in Al^{3+} complexing organic acids from decomposing crop residues (Hue, 1991; Yuan, 1980) may have been the most important cause of the P-driven mulch response in cereal growth at both Sahelian sites (Table 2). The lack of mulching effects on isotopically exchangeable P in the Sudanian zone may be explained by a combination of factors including (i) a lower deposition of cation-rich dust in this region, (ii) a quicker termite-driven turnover rate of crop residues (Buerkert et al., 2000), (iii) higher buffering capacities as a consequence of higher clay contents (Sinaj et al., 1997) and (iv) the higher concentration of dithionite-extractable Fe in the soil, particularly at Gaya (Table 1). The distribution of plant available P within the P pools of decreasing bioavailability, deduced from results of the isotopic exchange kinetics, seem particularly helpful to explain the lack of CR-induced increases in cereal growth at Gaya (Table 2). On this soil, higher in clay and amorphous oxides, organic compounds derived from applied CR mulch may have reduced the crystallisation of Fe and Al oxihydroxides and increased their reactive surfaces. On 1:1 clay minerals, such as kaolinite, which predominates at Gaya, P sorption capacity is well known to be a function of the specific surface area (Schwertmann and Herbillon, 1992). This should have led to the observed increase in the intensity (C_P) factor with SSP application, which increased P availability (Fig. 3).

Cropping system effects

The fact that cropping systems did not affect any of the measured factors controlling P availability at either site (Table 4) is in accordance with the TDM data. Despite their sandy texture, the pH buffering capacity of these soils apparently prevented a pH-induced rise of P availability in the bulk soil during the first 2 years of our study. This would also support the model of Bagayoko et al. (2000) which depicts higher N mineralisation values, early seedling infection with arbuscular mycorrhizae (AM) and site-specific lower levels of phytophagous nematodes as primary driving forces for rotation effects on these West-African soils. The findings of this study do not preclude the existence of measurable rotation-induced secondary effects on P availability and plant uptake in the rhizosphere of millet and sorghum but those effects may not have shown up in the bulk soil samples collected here.

Effects of phosphorus application

The consistent increases in the quantity (E_{1min}) and intensity (C_P) factors across sites with an annual broadcast application of SSP at 13 kg P ha^{-1} can explain the widespread agronomic effectiveness of this soluble P source in Sudano-Sahelian soils of West Africa where

P has been frequently found to be the most growth-limiting factor. The increase of available P with SSP13 is also a direct consequence of the positive P balance (annual P input minus P output by harvest) which at the low mulch rate amounted to between 3.3 kg P ha^{-1} at Gaya and 7.2 kg P ha^{-1} at Fada and at the high CR rate to between 4.0 and 6.8 kg P ha^{-1}, respectively. The high effectiveness of SSP placement (4 kg P ha^{-1}) in increasing cereal TDM appears to be due to the small but consistent increases in the quantity factor (E_{1min}) which may reflect a reduction in the proportion of P fertiliser fixed by the soil. Despite the large limitation to crop growth provided by the soils' low P status, the low correlations at the four trial sites between cereal TDM and either P-Bray (r = 0.019 to 0.57) or E_{1min} (r = 0.333 – 0.599) indicate how other plant nutrients and rainfall interact with P in determining final yield.

The site-specific effects of rockphosphate application mirrored the differences in rainfall, pH and clay content of the four soils. At Kara Bedji and Goberi, the drier Sahelian sites, rockphosphate application, despite the higher amount of P applied compared with SSP, was less effective in increasing E_{1min} and C_P but led to large increases in E_{1d-3m}. As such the P applied could only become available in the long-term. Every effort was made to prevent the powdery surface-applied rockphosphate from being blown away with the strong convective storms at the onset of the rainy season by mixing it with moist soil before application. Nevertheless, erosion-related losses may have occurred. The, compared with SSP fertilisation, particularly strong rise in the intensity value (C_P) with rockphosphate application at Gaya led to large increases in cereal yields at this site. The large C_P value was most likely the consequence of the abundant rainfall at this site and the particularly high dithionite-extractable Fe concentration of the soil (Table 1; Fig. 3). The lacking effect of rockphosphate application on either P fraction at Fada was consistent with the absence of a significant effect on cereal TDM. It was most likely caused by the relatively high pH and the low P buffering capacity at this site, factors, which have been studied previously by Chien and Menon (1995). With a high cation exchange capacity leading to less Ca leaching, Ca and carbonates added with rockphosphate probably caused the precipitation of exchangeable Al^{3+} as hydroxy Al-polymers resulting in the formation of newly active sorbing surfaces (Haynes and Swift, 1985) and consequently in reduced P availability. The low performance of rockphosphate regardless of the applied level of CR mulch may be explained in terms of inadequate sink strength (Bolan et al., 1990; Hedley et al., 1995).

Conclusions

The findings of this study are consistent with earlier reports (Fardeau and Jappé, 1980; Kato et al., 1995) which clearly demonstrated that the isotopic exchange kinetics method allows a better understanding of the effects of different sources and levels of mineral P fertilisers and soil amendments on crop growth. The method seems particularly useful on the severely P limited, poorly buffered and erosion prone sub-Saharan West African soils where soil amendments can lead to large pH changes. As such it can help to better predict site-specific differences in the efficiency of soil amendments as they affect TDM over years. However, the data with their sometimes large standard errors (Fig. 3) also indicate the extent to which the explanatory power of the method depends on representative soil sampling. The results also show that (i) for the soils under study legume rotations do not contribute significantly to increased P availability for cereals in the bulk soil and (ii) mulching with crop residues may enhance P nutrition of crops in the short-term, but only in combinations with mineral P it is likely to allow sustainable increases in crop production. The right choice of the P source will certainly be site-specific and depends on edaphic, climatic and economic factors.

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