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PHOSPHORUS PLACEMENT ON ACID ARENOSOLS OF THE WEST AFRICAN SAHEL

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SUMMARY

Phosphorus (P) deficiency is a major constraint to pearl millet (*Pennisetum glaucum* L.) growth on acid sandy soils of the West African Sahel. To develop cost-effective fertilization strategies for cash poor farmers, experiments with pearl millet were conducted in southwestern Niger. Treatments comprised single superphosphate hill-placed at rates of 1, 3, 5 or 7 kg P ha^{-1} factorially combined with broadcast P at a rate of 13 kg ha^{-1}. Nitrogen was applied as calcium ammonium nitrate at rates of 30 and 45 kg ha^{-1}. At low soil moisture, placement of single superphosphate in immediate proximity to the seed reduced seedling emergence. Despite these negative effects on germination, P placement resulted in much faster growth of millet seedlings than did broadcast P. With P application, potassium nutrition of millet was improved and seedling nitrogen uptake increased two- to three-fold, indicating that nitrogen was not limiting early millet growth. Averaged over the 1995 and 1996 cropping seasons, placed applications of 3, 5 and 7 kg P ha^{-1} led to 72 %, 81 % and 88 % respectively, of the grain yield produced by broadcasting 13 kg P ha^{-1}. Nitrogen application did not show major effects on grain yield unless P requirements were met. A simple economic analysis revealed that the profitability of P application, defined as additional income per unit of fertilizer, was highest for P placement at 3 and 5 kg ha^{-1}.

INTRODUCTION

Subsistence agriculture in the West African Sahel is based largely on the exploitation of fallow periods. Due to rapid population growth, the duration of these fallows is steadily decreasing leading to a widely recognized decline in soil fertility. Despite this, the use of mineral fertilizers in this region is among the lowest in the world and large negative nutrient balances at the field level are the consequence (Stoorvogel and Smaling, 1994). Yields of pearl millet (*Pennisetum glaucum* L.), the dominant crop in this region, are increased with the application of manure. This is an effective way to transfer nutrients from rangeland to cropped fields, and is practised intensively by most farmers. At the village level, however, available amounts of manure are

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sufficient to fertilize only a small proportion of the fields (Buerkert and Hiernaux, 1998).

Despite its low phosphorus (P) fixation capacity, the low concentration of plant-available P on the highly weathered, acid Sahelian soils (Bray-P typically 2–4 mg kg^{-1}) is, together with frequent drought spells and low soil nitrogen (N), a major constraint to crop growth (Bationo and Mokwunye, 1991a ; Bationo and Buerkert, 2001). Although the beneficial effects of P fertilizers are well known (Bationo *et al.*, 1992; Buerkert *et al.*, 2000), their use is severely limited by large fluctuations in grain prices, lack of capital and a poorly developed infrastructure (Vlek, 1990; Bationo *et al.*, 1997). In order to overcome the problem of continuous soil nutrient depletion, fertilizer application strategies have to be developed which (i) require only a small amount of capital, (ii) are highly efficient, (iii) are adaptable to farmers' management practices and (iv) have only a small risk of failure.

In Niger, a broadcast application of 15–20 kg P ha^{-1} was found to be adequate for optimum millet yields (Bationo and Mokwunye, 1991a). This recommendation, however, is seldom applied because most of the farmers in the region cannot afford such quantities of mineral fertilizers. The placement of P to young crops, therefore, should be an attractive alternative in the Sahel where most fields remain unploughed and millet is planted at an average density of only 5000 plant stands ha^{-1} (McIntire, 1986). Also, the quick-drying sandy top soil limits the dissolution of broadcast surface applied mineral fertilizers thereby restricting P diffusion into the rooting zone of seedlings.

Fertilizer placement has been recommended for maize in Malawi (Brown, 1966). Fox and Kang (1978) reported that yield-enhancing effects of localized P application to maize in southern Nigeria were observed only at sub-optimal P rates, especially during early growth stages. In western Niger, Davis *et al.* (1994) found that, at the same level of application, P placement increased millet yield more than did broadcasting. Their P rates of 22.5 and 45 kg ha^{-1}, however, were far too high for resource-poor farmers. Also in western Niger, however, earlier experiments by Bationo *et al.* (1992) showed no significant increase in millet yields when 13 kg P ha^{-1}were applied as single superphosphate (SSP) placed near the plant compared with a broadcast application of P of the same quantity.

To increase fertilizer use efficiency at low input rates, Rebafka *et al.* (1993) coated millet seeds with P fertilizer. This enhanced plant development but reduced emergence. Seed coating is technically not feasible under the current infrastructural conditions in Niger. The objective of the study reported here, therefore, was to test the effects of small quantities of P, placed in or close to the planting hill, on growth and nutrient uptake of millet.

MATERIALS AND METHODS

Field experiment with millet (experiment 1)

Site and treatment description. Rainfed millet was grown from 1994 to 1996 at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian

Centre (ISC), Sadoré, Niger (13°15′ N, 2°18′ E; 240 m asl) on a reddish acid sandy Labucheri soil. West *et al.* (1984) classified the soil as a Luvic Arenosol or a Psammentic Paleustalf, sandy, silicious and isohyperthermic. The field had been left under a naturally regenerating bush fallow for eight years prior to 1991 and from 1991 to 1993 it was cropped with millet as described by Buerkert and Stern (1995). In April 1991 the upper 0.2 m soil layer of the field was analysed according to standard methods, showing the following chemical properties: 4.15–4.90 pH-KCl, 1.4–5.9 mg kg^{-1} Bray-P, 0.2–0.5 cmolc kg^{-1}exchangeable potassium (K) and 1.8–3.1 g kg^{-1} organic carbon (C). From 1991 until 1993, half of the plots received P at an annual rate of 13 kg ha^{-1} as single superphosphate (SSP with 7.1 % P). After three years of P application, average soil Bray-P concentrations at 0–0.2 m depth were respectively 6.3 and 3.8 mg kg^{-1} soil in plots with and without P. In both treatments, however, water-available P in the same layer was about 470 μg kg^{-1} soil, irrespective of P application (Buerkert *et al.*, 2000).

Annual rainfall, distributed unimodally between April and October, was 794 mm in 1994, 491 mm in 1995 and 544 mm in 1996; the long-term average was 541 mm. Typically, highest precipitation occurs in July and August but the rainfall pattern is characterized by great temporal and spatial variability. Potential evapotranspiration can exceed 200 mm month^{-1} (Sivakumar *et al.*, 1993).

The layout, with 10 × 10 m plots as used from 1991 to 1993 (Buerkert and Stern, 1995), remained unchanged in 1994 when the following factorially combined treatments were applied: (i) two millet genotypes (the cultivar ICMV 89305 and the landrace Sadoré Local); (ii) three levels of surface-applied crop residues (CR) in the form of dry millet stalks broadcast at 500 and 2000 kg ha^{-1} and as surface-incorporated ash of 2000 kg CR ha^{-1}, amended by elemental sulphur at 3 kg ha^{-1}; (iii) N as calcium ammonium nitrate (CAN) at 0 and 30 kg ha^{-1}; (iv) two levels of broadcast P (P_{broad}) as SSP (0 and 13 kg ha^{-1}); and (iv) two levels of placed P (P_{placed}) as SSP (0 and 1 kg ha^{-1}). The placed SSP, equivalent to 1.3 g hill^{-1} at 10 000 hills ha^{-1}, was finely ground and deposited next to the seeds at about 0.05 m depth.

In 1995 and 1996 the experimental setup was modified, omitting the genotype Sadoré Local and the N treatment. Instead, a three-factorial design was imposed with (i) six levels of surface-applied crop residues (0 and 2000 kg ha^{-1} broadcast on former ash plots, 1000 kg ha^{-1} broadcast and banded on former 2000 kg ha^{-1} plots, 500 kg ha^{-1} broadcast and banded on former 500 kg ha^{-1} plots); (ii) two levels of broadcast phosphorus (P_{broad}) as SSP (0 and 13 kg ha^{-1}); and (iii) four levels of placed phosphorus (P_{placed}) as SSP (0, 3, 5 and 7 kg ha^{-1}). For the P placement, finely ground SSP was applied at a rate of 1 kg ha^{-1} as described above and the remainder of the dose was incorporated in equal splits to the left and right within 0.1 m distance of the planting hill. A basic N dressing of 30 kg ha^{-1} in 1995 and 45 kg ha^{-1} in 1996 was hill-placed as CAN to all plots. All treatments were arranged in a completely randomized design with two replications (Table 1).

In June of each year, millet seeds were sown manually at a spacing of 1 × 1 m. Based on *in-vitro* millet germination rates of 53 % in 1994, 73 % in 1995 and 81 % in 1996, the same amount of viable seed (equivalent to 50 kernels) was placed in each hill.

Table 1. Forms and rates of P application and treatment abbreviations for experiment 1 (millet field trial from 1994 to 1996) and experiment 2 (pot trial with millet dry seeding).

Experiment	P rate (kg ha^{-1})	Treatment	Description
1, 2	0	Control	No P application
1	13	P_{broad}	Broadcast P, slightly incorporated in the surface soil
1	1, 3, 5, 7	P_{placed}	Placed P, 1 kg P ha^{-1} (= 1.3 g SSP hill^{-1}) with the seed and the rest in equal splits 0.10 m to the side of the seed
2	13	P_{broad}	Broadcast P, 0.05 g SSP (kg soil)$^{-1}$ thoroughly mixed with the soil
2	1	P_{direct}	Placed P, 1.3 g SSP hill^{-1} placed with the seed
2	1	$P_{covered}$	Placed P, 1.3 g SSP hill^{-1} placed 0.01 m below the seed

Data collection. To measure treatment effects on the seedling survival rate at thinning, the number of living plants per plot was calculated from the dry weight of all thinned plants divided by the average dry weight of three samples of 100 plants, taking into account the three remaining plants hill^{-1} after thinning. The survival rate of millet seedlings was defined as the number of plants at thinning divided by 50 and multiplied by 100. At booting, approximately 50 days after sowing (DAS), and flowering (about 75 DAS), one randomly chosen planting row per plot was harvested to monitor treatment effects on total shoot dry matter (DM). At maturity (100–110 DAS), the remaining six rows of the plot were cut, but border rows and hills were excluded from sampling. To determine grain yield and DM, subsamples of straw and manually threshed millet panicles were oven-dried at 65 °C to constant weight. Weeding was done manually at thinning (23 DAS) and booting (50 DAS). To protect millet panicles against damage by the cotton stainer (*Dysdercus voelkeri*) and the scarabid beatle (*Rhinyptia infuscata*) the crop was treated twice during flowering with Decis® (deltamethrine) at a rate of 1 kg ha^{-1}.

The thousand-kernel weight (TKW) was calculated from the weight of three samples of 500 grains each. The threshing coefficient of millet panicles, defined as the ratio of grain to panicle dry weight, was determined. Net P fertilizer efficiency (NPFE; kg DM ha^{-1} per kg P ha^{-1}) was calculated as the difference of millet DM or grain yield produced at a given P rate and the respective yield of the control without P. The phosphorus uptake efficiency (PUE) was defined according to Sander *et al.* (1990) as the total grain yield (kg ha^{-1}) per unit P taken up in the DM (kg P ha^{-1}). The apparent recovery fraction (ARF) for fertilizer P was calculated according to Duivenbooden *et al.* (1996) as the ratio of total P uptake to total amount of applied P multiplied by 100.

Analysis of mineral nutrients. Subsamples of all dried plant material were ground to pass through a 2-mm sieve and analysed for N, P and K. Total N was determined with a Macro-N-Analyser (Heraeus, Bremen, Germany). For the analysis of P and K, the samples were ashed for four hours in a muffle furnace at 500 °C and the ash was dissolved in 1:30 (v/v) HCl. Phosphorus was determined colorimetrically (Hitachi U-3300 spectrophotometer) according to the vanado-molybdate method (Gericke and Kurmies, 1952) and K was analysed by flame emission photometry (Eppendorf ELEX 6361, Ismaning, Germany).

Calculation of net production values for millet grain. Based on the data obtained in 1995 and 1996, a simple linear net benefit function for millet grain yield as affected by P application of 0–13 kg ha^{-1} was calculated:

$$\text{Net benefit} = [\text{grain production (kg ha}^{-1}) \times \text{grain price (FCFA}^{\dagger}\text{ kg}^{-1})] - [\text{P rate (kg ha}^{-1}) \times \text{SSP price (FCFA kg}^{-1})]$$

Millet grain and fertilizer prices were based on average values obtained from surveys of local markets in southwest Niger during 1994 and 1996. The profit realized by farmers was assumed to be a function of (i) the value:cost ratio (VCR) defined as the ratio of the value of the additional grain produced to the cost of the fertilizer inputs necessary to achieve this yield, and (ii) the price ratio (PR) defined as the ratio of the cost of 1 kg fertilizer to the value of 1 kg millet (Bationo *et al.*, 1992).

Pot experiment on dry seeding with millet (experiment 2)

Two pot trials were conducted in 1995 to examine the effects of P placement on germination and early growth under controlled conditions. The pots contained 5 kg of a sandy, P-poor soil with the following chemical properties: 4.6 pH-KCl, 1.1 g kg^{-1}organic C, 4.1 mg kg^{-1} Bray-P, and 0.52 cmolc kg^{-1} CEC. The soil was taken from the top 0.2 m of a field neighbouring the ISC, air dried and sieved to pass through a 2 mm screen. In both trials the equivalent of 50 viable millet seeds (cultivar ICMV 89305) at a 73 % germination rate were placed in a 0.05 m-deep planting hole. All seedlings were harvested 12 days after the first irrigation. Shoots were counted and clipped off at the soil surface and the roots were washed from the soil. Shoot and root samples were oven-dried at 65 °C to constant weight to determine their dry matter.

In the first trial, designed to mimic dry seeding conditions practised by many Sahelian farmers, the seeds remained without irrigation initially. It was only at 14 DAS that 0.5 l deionized water pot^{-1} (equivalent to 20 mm) was applied. On 15 and 18 DAS each, 0.25 l deionized water pot^{-1} (equivalent to 10 mm) was added and, thereafter, no further irrigation occurred. In the second trial, set up to examine P effects on millet germination, all pots were watered daily to field capacity (10 % w/w) until the seedlings were harvested. Four levels of P were applied (Table 1): 0 g pot^{-1} (control), 1.3 g SSP pot^{-1} (equivalent to 1 kg P ha^{-1}) hill-placed directly with the seed (1 P_{direct}), 1.3 g SSP pot^{-1} hill-placed 0.01 m below the seed (1 $P_{covered}$) and 0.25 g SSP pot^{-1} (equivalent to 13 kg P ha^{-1}) broadcast (13 P_{broad}). The SSP of the P_{broad} treatment was thoroughly mixed with the soil to mimic an incorporated

†Currency of Niger, 'Franc de la Communauté Francophone de l 'Afrique'.

Table 2. Effect of placed (P_{placed}) SSP application (kg P ha^{-1}) on the survival rate (%) of field-grown millet seedlings, calculated as the number of seedlings 23 days after sowing divided by the number of viable seeds per hill, Sadoré, Niger, 1994 to 1996 (experiment 1).

P_{placed} (kg ha^{-1})	0	1	3	5	7	
Year	Seedling survival rate (%)					*sed* §
1994	27	22	n.d.	n.d.	n.d.	2.1
1995	35	n.d.	29	26	29	2.5
1996	31	n.d.	20	21	20	1.3

§ Standard error of the difference.
n.d. = not determined.

Table 3. Effects of dry seeding in combination with different forms of SSP application (kg P ha^{-1}) under water limited and well watered conditions on the survival rate of millet seedlings (%), calculated as the number of viable seedlings 12 days after sowing divided by the number of viable seeds per hill. The finely ground SSP was applied either directly in the planting hole (1 kg P ha^{-1} direct), placed 0.01 m below the seeds and covered with a layer of sand (1 kg P ha^{-1} covered) or homogeneously mixed with the soil (13 kg P ha^{-1} broad) to mimic a well incorporated broadcast application. Pot trial, Sadoré, Niger, 1995 (experiment 2).

		1 P_{direct}	1 $P_{covered}$	13 P_{broad}	
SSP (kg P ha^{-1})	Control	Seedling survival rate (%)			*sed* §
limited water	68	5	34	63	8.8
well watered	81	17	85	81	3.1

§ Standard error of the difference.

fertilizer application. All P was applied as finely ground SSP, and treatments were replicated ten times.

Statistical analysis

All data were subjected to analysis of variance using GENSTAT 5 release 3 (Lawes Agricultural Trust, 1993). Probabilities of treatment effects and standard errors of the difference (*s.e.d.)* were reported with the respective means.

RESULTS

Seedling survival

In experiment 1, survival rates of millet seedlings in control treatments ranged from 27–35 % over the three years (Table 2). Broadcast P did not affect seedling survival in any year. Placed application of SSP, however, reduced the survival rate of millet seedlings compared with plots without P placement, irrespective of the amount of P, by 20 % in 1994 and 1995 and by 33 % in 1996 (Table 2). Similar results were obtained in experiment 2. The application of SSP at 1.3 g pot^{-1} (equivalent to 1 kg P ha^{-1}) directly with the millet seed had detrimental effects on germination (Table 3). Survival rates of millet seedlings with 13 P_{broad} were similar to those of the control both at 40

Table 4. Shoot dry matter and shoot P concentration of millet seedlings at thinning, 23 days after sowing, as affected by broadcast (0 and 13 kg P ha^{-1}) and placed (0 and 1 kg P ha^{-1}) phosphorus (P). Sadoré, Niger, 1994 (experiment 1).

$P_{broadcast}$ (kg ha^{-1})	0		13		
P_{placed} (kg ha^{-1})	0	1	0	1	*sed*§
Shoot dry weight (mg $plant^{-1}$)	84	106	98	134	17.2
Shoot P concentration (mg g^{-1})	2.3	2.5	2.9	3.1	0.16

§ Standard error of the difference.

and 100 mm applied water. With those same amounts of applied water, SSP applied directly with the millet seed (1 P_{direct}) decreased the survival rate to 7 and 21 % of the control, respectively. Separating the fertilizer from the seed by a thin layer of sand (1 $P_{covered}$) strongly improved seedling survival compared with 1 P_{direct}. Regular water supply after the onset of germination increased the survival rate with $P_{covered}$ to the level of the control, but hardly affected millet germination in the 1 P_{direct} treatments.

Early millet growth

In the 1994 field experiment, broadcast P at 13 kg ha^{-1} increased millet DM at thinning by 17 % and P placement at 1 kg ha^{-1} by 26 % compared with the unfertilized control (Table 4). The combination of 13 P_{broad} and 1 P_{placed} resulted in DM increases of 60 % compared with the control and of 26 % compared with the 13 P_{broad}-treatment alone. In 1995 and 1996, the 13 P_{broad} application increased DM at thinning by 66 % and 62 % respectively compared with the control (Table 5) whereas the placed application of 3 kg P ha^{-1} more than doubled DM of millet seedlings in both years. The combination of 13 P_{broad} and 3 P_{placed} almost tripled DM. With adequate rainfall after sowing in 1995, 5 kg P_{placed} ha^{-1} led to similar DM levels compared with 3 P_{placed}. With a post-sowing drought in 1996, however, seedling DM from treatments receiving the higher level of placed P was reduced by 20 %. In both years, the application of 7 P_{placed} led to lower DM than that from 3 P_{placed} treatments (Table 5).

Nutrient acquisition of millet seedlings

Phosphorus application not only increased early millet growth, but also affected shoot P concentration. In experiment 1 in 1994, shoot P increased by 8, 26 and 31 % with 1 P_{placed}, 13 P_{broad} and the combination of 1 P_{placed} and 13 P_{broad} respectively, compared with the control (Table 4). This translated into a P uptake per seedling of 0.19 mg for the control, 0.28 mg for 1 P_{placed} or 13 P_{broad} and of 0.42 mg for the combination of both. In 1995 and 1996, however, P placement at a rate of 3, 5 or 7 kg ha^{-1} significantly increased shoot P concentrations of young millet, whereas P_{broad} affected shoot P concentration only in 1995 (Table 5). Compared with 3 P_{placed} in 1995 and 1996, P uptake per seedling with 13 P_{broad} was lower by 26 and 45 % respectively and with the combination of 3 P_{placed} and 13 P_{broad} was higher by 39 and 30 % respectively.

Table 5. Dry matter, phosphorus (P), nitrogen (N) and potassium (K) concentration of millet shoots at thinning, 23 days after sowing, as affected by the rate (kg P ha^{-1}) of broadcast (P_{broad}) and placed (P_{placed}) P application. Sadoré, Niger, 1995 and 1996 (experiment 1).

	Dry matter (mg $plant^{-1}$)				P concentration (mg g^{-1})				N concentration (mg g^{-1})				K concentration (mg g^{-1})			
Year	1995		1996		1995		1996		1995		1996		1995		1996	
P_{broad} (kg ha^{-1})	0	13	0	13	0	13	0	13	0	13	0	13	0	13	0	13
P_{placed} (kg ha^{-1})																
0	137	227	66	107	2.4	2.9	1.8	2.1	34.4	33.4	34.4	35.9	33.8	39.3	31.8	32.6
3	296	386	158	194	3.0	3.2	2.5	2.7	36.2	33.9	38.3	38.4	41.4	41.5	33.5	37.4
5	305	380	126	149	3.1	3.5	2.8	3.0	34.5	32.9	36.6	35.8	41.8	40.9	36.9	36.9
7	219	317	136	149	3.1	3.6	3.3	2.8	36.3	32.8	37.6	36.6	38.5	39.0	33.0	35.3
sed[§]	51.5		26.9		0.13		0.24		3.1		2.19		2.08		2.32	

[§]Standard error of the difference.

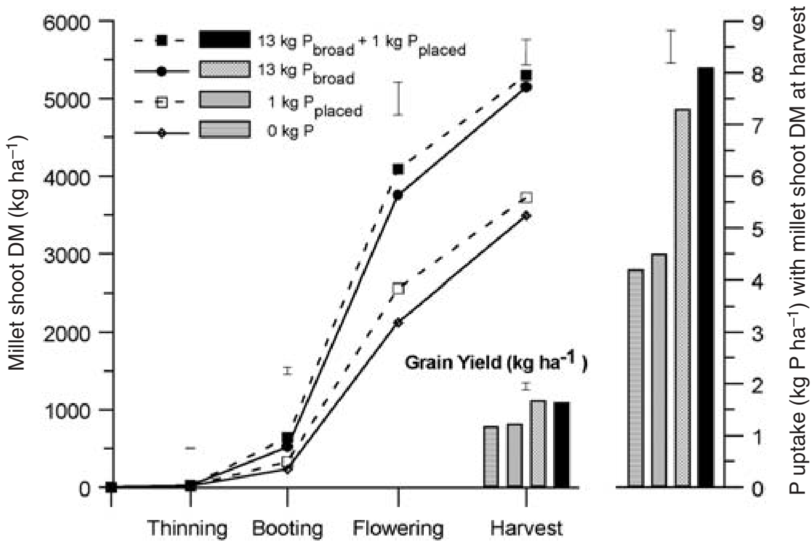

Figure 1. Time course of millet shoot dry matter (DM) development, grain yield (kg ha^{-1}) and total P uptake (kg ha^{-1}) with shoot DM, as affected by broadcast (0 and 13 kg P ha^{-1}) and placed (0 and 1 kg P ha^{-1}) phosphorus (P) application. Sadorè, Niger, 1994 (experiment 1). Vertical bars indicate one standard error of the difference.

Phosphorus application had only minor effects on N concentration in seedlings. They ranged between 33 and 38 mg g^{-1} (Table 5). Shoot N uptake per seedling increased with shoot dry weight from 4.7 mg N in 1995 and 2.3 mg N in 1996 (without P) to 13.1 and 7.5 mg N respectively with the combined application of 13 P_{broad} and 3 P_{placed}.

In contrast to N, K concentration in millet seedlings at 23 DAS was markedly higher with P application (Table 5). Lowest K concentrations were found in treatments without P application, resulting in shoot K uptake of 4.6 and 2.1 mg per seedling in 1995 and 1996 respectively. The application of 13 P_{broad} combined with 3 P_{placed} increased shoot K concentrations by 23 % (in 1995) and 18 % (in 1996) compared with the control; the respective shoot K uptake amounted to 16.0 and 7.3 mg K respectively. In 1995, applications of 3 or 5 P_{placed} alone and of 13 P_{broad} increased K concentrations in millet by 23, 24 and 16 % respectively. With the early season drought in 1996 neither 13 P_{broad} nor 3 P_{placed} affected K shoot concentrations, whereas 5 P_{placed} increased it by 16 %.

Vegetative millet growth

Despite its large impact on early seedling growth, the 1994 application of 1 P_{placed} had only minor effects on millet growth (Figure 1). From the booting stage onward, the amount of millet DM from plots receiving broadcast P was greater than from plots receiving 1 P_{placed}. In 1995 and 1996, however, both placed and broadcast P applications had highly significant effects on DM at booting (51 DAS) and flowering

Table 6. Shoot dry matter (DM) of millet at 51 days after sowing (DAS) and flowering (77 DAS), as affected by the rate of broadcast (P_{broad}) and placed (P_{placed}) phosphorus (P) application. Sadoré, Niger, 1995 and 1996 (experiment 1).

	DM (kg ha^{-1}) at booting				DM (kg ha^{-1}) at flowering			
Year	1995		1996		1995		1996	
P_{broad} (kg ha^{-1})	0	13	0	13	0	13	0	13
P_{placed} (kg ha^{-1})								
0	399	917	187	409	1414	3375	971	2156
3	806	1314	489	842	2708	4499	1730	3213
5	785	1210	497	751	2848	4136	1929	2671
7	1020	1037	515	602	3108	3975	2143	2433
sed§	133.0		100.3		403.1		262.8	

§ Standard error of the difference.

Table 7. Phenological parameters of millet at flowering 77 days after sowing as affected by the rate of broadcast (P_{broad}) and placed (P_{placed}) phosphorus (P) application. Shown is the number of hills without panicles as percentage of all hills, the average number of millet panicles per hill, calculated for hills having at least one visible panicle and the percentage of panicles at anthesis and post anthesis. Sadoré, Niger, 1995 and 1996 (experiment 1).

	Hills without panicles (%)				Number of panicles hill^{-1}				Panicles at and post anthesis (%)			
Year	1995		1996		1995		1996		1995		1996	
P_{broad} (kg ha^{-1})	0	13	0	13	0	13	0	13	0	13	0	13
P_{placed} (kg ha^{-1})												
0	38	9	64	42	2.0	2.9	1.4	2.3	47	71	10	21
3	8	2	32	18	2.7	3.4	2.0	2.7	74	85	28	41
5	5	5	30	22	2.7	3.4	2.1	2.6	76	84	23	32
7	6	3	28	22	2.9	3.2	2.2	2.6	74	82	27	30
sed§	5.1		6.0		0.2		0.2		4.7		4.5	

§ Standard error of the difference.

(77 DAS). At booting, millet DM with 13 P_{broad} was similar to that of the placed P application (Table 6). Compared with the unfertilized control, 13 P_{broad} alone increased millet DM at flowering by 130 %, whereas DM was roughly doubled with placed applications of 3, 5 or 7 kg P ha^{-1}. In both years the combination of 13 P_{broad} and 3 P_{placed} tripled millet DM.

Compared with the control, the phenological development of millet plants at flowering was more advanced with all rates and both modes of P application (Table 7). Plots without P also had a significantly higher percentage of hills without panicles compared with plots that had received some form of P. In both years the lowest number of hills without panicles was obtained with the combination of 13 P_{broad} and 3 P_{placed}. Individually, placed and broadcast P also increased the number of panicles per hill. Phosphorus application led to large increases in the percentage of panicles at flowering and to early grain filling. In plots without P application, only 47 and 10 % of the panicles were at or beyond flowering in 1995 and 1996 respectively. The most

Table 8. Effects of broadcast (0 and 13 kg P_{broad} ha^{-1}) and hill placed (0, 3, 5 and 7 kg P_{placed} ha^{-1}) phosphorus (P) on millet shoot dry matter (DM) and grain yield at maturity. Sadoré, Niger, 1995 and 1996 (experiment 1).

	Shoot DM (kg ha^{-1})				Grain yield (kg ha^{-1})			
Year	1995		1996		1995		1996	
P_{broad} (kg ha^{-1})	0	13	0	13	0	13	0	13
P_{placed} (kg ha^{-1})								
0	1951	4012	2413	4585	532	1138	641	1240
3	3157	4830	3216	5314	864	1382	846	1279
5	3341	4713	3790	5180	937	1425	996	1295
7	3498	4381	4041	4889	1018	1287	1074	1331
sed[§]	313.5		346.3		91.9		89.0	

[§] Standard error of the difference.

advanced phenological development was observed with the combination of placed and broadcast P, followed by the application of placed and then of broadcast P.

Millet grain yield and shoot dry matter at maturity

Compared with the control, the application of 13 P_{broad} increased millet DM at maturity by 47 % in 1994 (Figure 1), by 106 % in 1995 and by 90 % in 1996 (Table 8). In 1994 neither 1 P_{placed} alone or in combination with 13 P_{broad} affected DM yield. However, P placement at higher rates significantly increased millet DM. Compared with the control, the placed application of 3 or 5 kg P ha^{-1} respectively increased millet DM by 62 % and 71 % in 1995 and by 33 % and 57 % in 1996. The combination of 13 P_{broad} with 3 P_{placed} led in both these years to the highest TDM production (Table 8). Across 1995 and 1996, the average additional DM produced per unit fertilizer decreased from 355 to 277 kg DM kg^{-1} P with 3 P_{placed}, to 227 kg DM kg^{-1} P with 5 and 7 P_{placed} and to 163 kg DM kg^{-1} P with 13 P_{broad}.

Grain yields mirrored DM production for all three harvests (Table 8, Figure 2). Averaged over the 1995 and 1996 cropping seasons, placed applications of 3, 5 and 7 kg P ha^{-1} led to 72, 81 and 88 % of the grain DM produced with 13 P_{broad}.

Thousand-kernel weight (TKW) and nutrient concentration of millet at maturity

Compared with the control in 1994, neither TKW nor grain P concentration was affected by 1 P_{placed} (data not shown). On the other hand, though 13 P_{broad} had only minor effects on TKW, it increased grain P concentration by 18 %. In 1995 and 1996, however, TKW and grain P concentrations were significantly increased by placed applications of 3, 5 or 7 kg P ha^{-1} and by 13 P_{broad} (Table 9). Whereas 5 P_{placed} increased average grain yield by 17 % and grain P concentration by 13 %, the application of 13 P_{broad} increased both parameters by about 20 %. The combination of broadcast with P placement did not affect grain yield but increased grain P concentration by 38 % compared with the unfertilized control. The amount of P stored in a single grain was 32 and 46 % higher than the control following the application of 5 P_{placed} and 13 P_{broad} respectively.

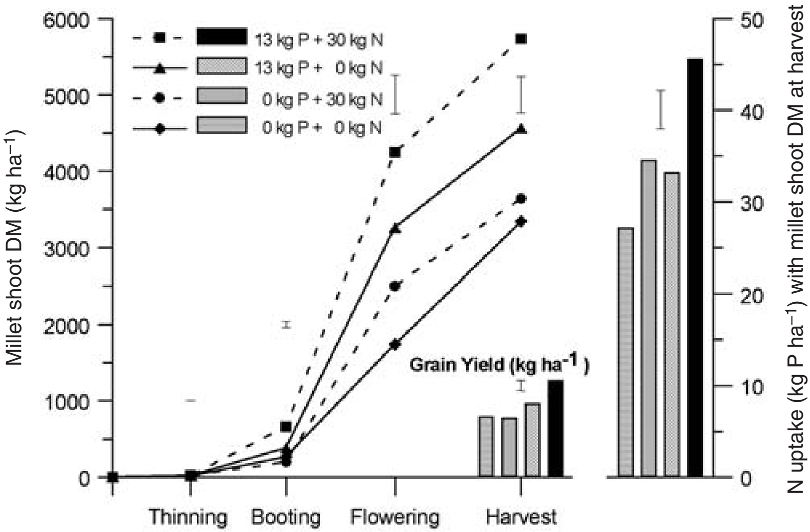

Figure 2. Time course of millet shoot DM (kg ha^{-1}) and grain yield (kg ha^{-1}) at final harvest as affected by the application of broadcast phosphorus (P) at 0 and 13 kg P ha^{-1} in combination with or without nitrogen (N) at 0 and 30 kg N ha^{-1}. Sadoré, Niger, 1994 (experiment 1). Vertical bars indicate one standard error of difference.

Table 9. Effects of broadcast (0 and 13 kg P_{broad} ha^{-1}) and hill placed (0, 3, 5 and 7 kg P_{placed} ha^{-1}) phosphorus (P) on thousand-kernel weight (TKW) and grain P concentration of millet at maturity. Sadoré, Niger, 1995 and 1996 (experiment 1).

	TKW (g)				Grain P concentration (mg g^{-1})			
Year	1995		1996		1995		1996	
P_{broad} (kg ha^{-1})	0	13	0	13	0	13	0	13
P_{placed} (kg ha^{-1})								
0	6.7	8.0	7.1	8.6	2.6	3.2	3.3	3.9
3	7.3	8.0	7.8	8.7	2.8	3.6	3.2	4.6
5	7.6	8.4	8.5	8.7	2.9	3.6	3.8	4.4
7	7.8	8.1	8.4	8.4	2.9	3.7	4.0	4.4
sed§	0.25		0.21		0.11		0.22	

§ Standard error of the difference.

Total P uptake

In 1994, the total P uptake in harvested unfertilized millet (Figure 1) was much higher than in the following two years (Table 10). In 1995 and 1996, the application of 1 P_{placed} did not significantly enhance P uptake, but it increased to between 7 and 8 kg P ha^{-1} with 13 P_{broad}. The ARF for P in these two years was 113 and 123 % for 3 P_{placed} respectively, indicating that soil P contributed up to 20 % to the total P uptake in millet DM. The application of 5 P_{placed} resulted in an ARF of between 75 % and 100 % and the recovery rate dropped to under 50 % with the application of 13 P_{broad} or with a combination of broadcast and placed P. In 1995 and 1996 PUE was highest for 5 P_{placed} and 3 P_{placed} (Table 10).

Table 10. Effects of broadcast (0 and 13 kg P_{broad} ha^{-1}) and hill placed (0, 3, 5 and 7 kg P_{placed} ha^{-1}) phosphorus (P) application on total P uptake and P uptake efficiency (PUE) in total dry matter of millet at maturity. Sadoré, Niger, 1995 and 1996, (experiment 1).

	Total P uptake (kg P ha^{-1})				PUE (kg grain per kg P uptake)			
Year	1995		1996		1995		1996	
P_{broad} (kg ha^{-1})	0	13	0	13	0	13	0	13
P_{placed} (kg ha^{-1})								
0	2.0	5.0	2.9	6.6	249	235	195	192
3	3.4	7.1	3.7	8.5	252	205	230	153
5	3.7	6.9	5.0	7.9	259	214	205	170
7	4.1	6.5	5.7	7.9	254	210	188	179
sed§	0.5		0.5		9.1		14.2	

§ Standard error of the difference.

Phosphorus and N effects on millet growth and N uptake

The total dry matter of unfertilized millet was exceptionally high in 1994 (Figure 2). Compared with the control without both P and N, the application of N alone barely increased DM, but it increased total N uptake of millet by 27 %. When compared with the application of N alone, the addition of P increased DM by 25 % though straw and grain had lower N concentrations; the total N uptake per hectare, however, was similar. With P application the addition of N resulted in an 80 % yield increase and an additional N uptake of 30 %.

Net production value of millet grain under different levels of P application

Millet grain yield was highly correlated with P application (Figure 3). With 70–90 kg kg^{-1}, 3 P_{placed} and 5 P_{placed} gave the highest grain yield increases per unit P applied. A broadcast application of 13 kg P ha^{-1} resulted in a grain yield increase of 40–50 kg kg^{-1} applied P. The additional net production value reached its maximum just above a P application rate of 13 kg ha^{-1} (data not shown). Highest VCRs were obtained for 3 P_{placed} and 5 P_{placed} (Table 11). VCR values were lowest for 13 P_{broad}, particularly at price ratios above 1.0 representing high fertilizer and low millet grain prices.

DISCUSSION

Early plant growth

Broadcast P application effectively increased DM development of millet seedlings (Tables 3 to 5). This supports results from previous experiments on the same field that showed an increase in millet seedling DM after a broadcast application of 13 kg P ha^{-1} of 80 and 67 % in 1992 and 1993 respectively (Buerkert *et al.*, 1997). The rather small effects of broadcast P in 1994 (Table 4) were probably due to the intense rainfall that occurred soon after sowing. These rains caused not only visible growth problems for the seedlings but also large surface runoff, possibly removing a portion of the broadcast fertilizer. Despite the negative effects on germination, placed

Table 11. Effects of hill placed (3, 5 and 7 kg P ha^{-1}) and broadcast (13 kg P ha^{-1}) phosphorus (P) application on the value-cost-ratio (VCR) and price ratio (PR) between millet grain and single superphosphate (SSP) fertiliser. Calculations are based on grain yields of on-station trials at 10 000 hills ha^{-1} and were then extrapolated to the traditional farmers' practice of 5000 hills ha^{-1}.

Grain price (FCFA kg^{-1})	50	75	75	75	100
Fertilizer costs (FCFA kg^{-1})	100	100	75	50	50
Price ratio	2.0	1.3	1.0	0.7	0.5
Applied P fertilizer (kg ha^{-1})	Value-Cost-Ratio at 10 000 hills ha^{-1}				
3	3.1	4.7	6.2	9.3	12.4
5	2.8	4.3	5.7	8.5	11.3
7	2.6	3.8	5.1	7.7	10.3
13	1.7	2.6	3.5	5.2	7.0
Applied P fertilizer (kg ha^{-1})	Value-Cost-Ratio at 5000 hills ha^{-1}				
3	1.6	2.3	3.1	4.7	6.2
5	1.4	2.1	2.8	4.3	5.7
7	1.3	1.9	2.6	3.8	5.1
13	0.9	1.3	1.7	2.6	3.5

§ Standard error of the difference.

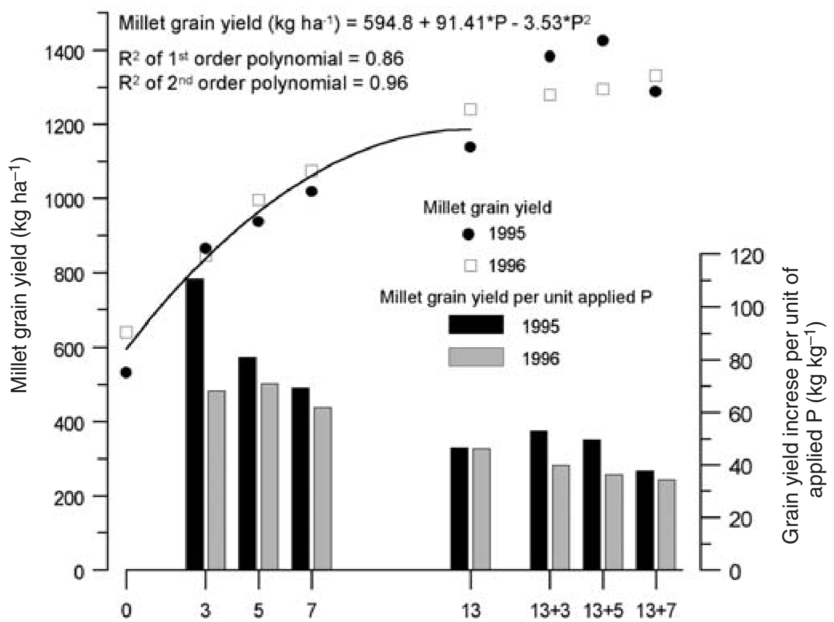

Figure 3. Millet grain yield (kg ha^{-1}) and grain yield increase per unit P fertiliser as affected by 0 and 13 kg P ha^{-1} broadcast (P_{broad}) and 0, 3, 5 and 7 kg P ha^{-1} placed (P_{placed}) phosphorus (P) application. The millet grain production function describes the correlation between the rate of P fertiliser and the millet grain produced over the range of 0 to 13 kg P ha^{-1} applied. Sadoré, Niger, 1995 and 1996 (experiment 1).

applications of 1 to 5 kg P ha^{-1} produced much larger millet seedling DM than 13 P_{broad}.

It appears that the level of available P in the proximity of the plant stand was more important for millet seedling development than was the total quantity of applied P. This hypothesis is further supported by the DM increase with a combination of broadcast and placed P application (Tables 4 to 6). Richards *et al.* (1985) showed that placing small amounts of fertilizer with maize seed increased seedling DM more than did broadcast P and, even in combination with broadcast P fertilizer, had beneficial effects on seedling growth. Coating millet seeds with P increased several-fold both the growth and P uptake of seedlings (Rebafka *et al.*, 1993).

Nutrient acquisition of millet seedlings

Critical P concentrations in the shoot tissue of young sorghum plants are around 2.5 mg g^{-1} and non-limiting P levels are above 3 mg g^{-1} (Reuter and Robinson, 1988; Jones *et al.*, 1991). Based on these reports, millet shoots without P (Tables 4 and 5) appeared at thinning to be clearly P deficient. The particularly low P concentrations of 1996 may have been the consequence of both reduced availability and mobility of P due to low soil moisture after sowing. Nevertheless with P placement, seedling P uptake was three to four times higher than in unfertilized control plots.

With the exception of 1994, P placement alone led to higher plant P than did 13 P_{broad} (Tables 4 and 5). The combination of both modes of P addition further increased shoot P concentration. This supports earlier results for maize (Fox and Kang, 1978; Eghball and Sander, 1989). The immediate effect of P placement on plant growth and P uptake of millet seedlings is particularly noteworthy given that these plots had received broadcast P (as SSP) at a yearly rate of 13 kg ha^{-1} since 1991.

Bray-P concentrations in unfertilized acid sandy soils of Niger barely exceed 3 mg kg^{-1}, whereas about 8 mg kg^{-1} has been determined as the critical P level for optimum growth of millet (Bationo and Mokwunye, 1991a). To reach this level of P, however, repeated fertilizer application is required. Only the three-fold application of 13 kg P_{broad} ha^{-1} raised the Bray-P concentration in the upper 0.2 m of the soil from 2.8 to 5.6 mg P kg $soil^{-1}$ (Buerkert *et al.*, 2000). Given that millet seeds are small (< 10 mg), a P reserve of only about 20 μg $seed^{-1}$ is very low. The crop, therefore, depends heavily on an external supply of P soon after emergence (Rebafka *et al.*, 1993). Phosphorus uptake of a single millet seedling within the first three weeks exceeds the seed reserves by 100 to 300 μg $plant^{-1}$ but P uptake can be as high as 900 to 1300 μg $plant^{-1}$ with placed applications of 3 or 5 kg P ha^{-1} and adequate precipitation after sowing (Table 4 and 5). Rebafka *et al.* (1993) reported similar P uptake for P-coated millet seedlings.

At 23 DAS, N concentration in millet seedlings was hardly affected by either the mode or amount of P application, or by seedling DM (Table 5). Until thinning, no N fertilizer had been applied, therefore plant N uptake was totally dependant on soil N reserves. According to Herrmann *et al.* (1994), soil nitrate at the beginning of the rainy season is decisive for millet establishment and explains a good proportion of the typical early season growth variability. This conclusion was based, however, on correlations between soil chemical parameters and millet DM at harvest; it did not consider nutrient concentrations of seedlings. In contrast, the results of the present study (Table 5) indicate that N concentration was barely correlated with early DM of millet, and soil P rather than N appeared to be the main growth-limiting nutrient. Nitrogen concentrations of 32–38 mg g^{-1} have been shown to be critical for millet (Reuter and Robinson, 1988; Jones *et al.* 1991), thus the reported N concentrations in millet seedlings do not appear to be particularly low. Plant N uptake increased with P-induced plant growth two- to three-fold, providing evidence that N availability was not a limiting factor for millet seedling development.

Phosphorus application also led to large changes in the K status of early millet, particularly when P was placed near the seed. Potassium threshold levels for young sorghum plants have been reported to range between 30 and 45 mg g^{-1} (Jones *et al.*, 1991) and thus the K concentrations of millet seedlings as presented in Table 5 can be considered adequate. The simultaneous increases of P and K concentrations in millet tissue, due to P application, likely reflects increased root growth with placed P application as opposed to broadcast P, leading to increased K uptake via mass flow.

Yield parameters

On the low-fertility soils of the Sahel any setback in early millet development can seldom be compensated for during subsequent periods of exponential biomass development. Within the first 30 days of millet growth, the tiller buds and panicle meristems are initiated and the floral primordia formed (Maiti and Bidinger, 1981). Early growth conditions, therefore, directly affect leaf area index, number of panicles per plant stand, final grain yield and DM (Azim-Ali *et al.*, 1984; Carberry *et al.*, 1985).

Placed P appeared to be particularly effective in enhancing early millet growth. Beyond the stage of booting (around 50 DAS), however, its effects tended to decline compared with broadcast P (Tables 6 and 8). Similar observations were reported for maize after the ten-leaf stage (Eghball and Sander, 1989). In sorghum, the application of P tended to increase tillering and hence the number of harvested heads (Sander *et al.*, 1990). For millet, Rockström and de Rouw (1997) reported that P fertilization improved the drought tolerance at panicle initiation and grain filling. Similar findings were reported for seed coating in millet (Rebafka *et al.*, 1993), that is accelerated leaf appearance, tillering and DM accumulation despite early setbacks at germination. With only 25 to 40 % of the potential number of millet panicles being developed under P deficiency (Table 7), adequate P is crucial for increasing the number of panicles per plant and hence potential yield per unit area.

Increased soil fertility led to faster and more vigorous millet development, which in the Sahel, with its frequent late season droughts, can be of paramount importance to reduce the risk of crop failure (Winkel *et al.*, 1997).

Total dry matter and grain yield

Although the broadcast application of mineral P fertilizers at 13 kg ha^{-1} may double millet yields (Table 8 and Figure 1), their use by Sahelian farmers is severely limited by a lack of financial resources (Bationo *et al.*, 1997). Placed application of 5 kg P ha^{-1} achieved 65 % of the yield increase obtained with 13 P_{broad} (Table 8) thus resulting in a significantly higher fertilizer-use efficiency than with broadcast P (Table 10). Buerkert and Hiernaux (1998) reported similar effects from the application of 4 kg P as compound NPK fertilizer.

Although the response of millet to applied mineral N can be substantial with non-limiting soil moisture (Bationo and Mokwunye, 1991a), this study's data show that N application did not have major effects on millet yield unless P requirements were met (Figure 2). The N uptake by the total biomass was approximately 35 kg ha^{-1} without P application, increasing to 45 kg ha^{-1} with both P and N fertilization. These figures indicate that the recommended application rate of 30 kg N ha^{-1} (Bationo *et al.*, 1992) may sustain a millet shoot DM production of about 3000 kg ha^{-1}, but is insufficient to balance the crop's N removal at more intensive levels of production. Total N uptake by the millet biomass is reported to range between 23 kg N ha^{-1} without P application and 60 kg N ha^{-1} with 13 kg P ha^{-1} (Bationo and Mokwunye, 1991b). In this context, losses due to ammonia volatilization and leaching are not considered. They may, however, contribute considerably to the N balance. Christianson *et al.* (1990) and Bationo and Mokwunye (1991a) reported that, in extreme cases, millet absorbed only 20 % of applied fertilizer N, about 30 % was immobilized in the soil and up to 50 % was lost by volatilization or leaching. Recent measurements in southwest Niger indicated annual leaching losses of N in the order of 8–10 kg ha^{-1} (Herrmann, 1996) and Hafner *et al.* (1993) reported N losses by volatilization of up to 36 % of the fertilizer application rate. Under farmers' conditions such negative balances may only be partly compensated for by N inputs from rain and dust deposition at the respective amounts of 3.5 and 3 kg ha^{-1} a^{-1} (Herrmann, 1996). In comparison, biological N_2-fixation by free-living rhizosphere bacteria may contribute as much as 20 kg N ha^{-1} a^{-1} (Hafner *et al.*, 1993).

Concentration and uptake of P

Phosphorus concentrations in millet grain produced by 14 farmers at five locations in southwest Niger ranged between 2.3 mg g^{-1} and 5.5 mg g^{-1} with a median of 3.2 mg g^{-1} (Buerkert *et al.*, 1998). This compares to the P concentrations observed in the present study for grain without P application. Broadcast P at 13 kg ha^{-1} increased the P concentration in millet grain by between 2.6 and 3.3 mg g^{-1} (Table 9). Other authors reported similar results (Rebafka *et al.*, 1994; Duivenbooden *et al.*, 1996).

CONCLUSIONS

The adoption of innovative methods to sustain and improve millet production in sub-Saharan West Africa depends on the feasibility of the technique, the potential income gain from its implementation and the farmers' overall socio-economic situation. The consequence of subsistence-level farming, which in the past had been hidden by prolonged fallow periods, is the steady productivity decline of Sahelian soils. Counteracting soil nutrient depletion and subsequent land degradation while supplying enough food for the growing population of the Sahel, undoubtedly requires the application of external inputs. For millet, P placement with the seed offers an effective approach to overcome P deficiency. The application of SSP, however, entails the risk of salt injury to seedlings, especially under drought conditions. This problem might be avoided by using finely ground compound NPK fertilizer instead of SSP. Phosphorus placement at low rates can be easily adapted to the individual planting pattern of each farmer but it does not restore a soil's P reserves. To this end the combination of placed soluble P with locally available rockphosphate as a slow-release P source might offer a way to increase concurrently crop productivity and soil P reserves.

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