ELSEVIER
Field Crops Research 36 (1994) 113–124
Field Crops Research

Short- and long-term effects of crop residues and of phosphorus fertilization on pearl millet yield on an acid sandy soil in Niger, West Africa

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(Received 18 March 1993; accepted 11 January 1994)

Abstract

Field experiments were conducted during the rainy seasons of 1990 and 1991 on an acid sandy soil (Luvic Arenosol) in Niger, to assess long-term (since 1986) and short-term (since 1990) effects of millet straw (crop residues) at different amounts (2 t and 6 t ha^{-1}) and modes of application (incorporation, mulching and burning), and of phosphorus (P) fertilization on dry matter yield of pearl millet [*Pennisetum glaucum* (L.) R. Br.]. Especially long-term, but also short-term application of crop residues increased dry matter yield of pearl millet by more than 60%, whereas their omission decreased yield immediately. Compared to mulching or burning, higher yields were obtained with incorporation of crop residues. When crop residues were applied as mulch, dry matter yield was increased to the same extent by 2 t and 6 t ha^{-1}. Similar dry matter yields were achieved with crop residues (−P) to those with P fertilizer only. An additional yield increase could be obtained by simultaneous application of crop residues and P. Without crop residues, potassium (K) concentrations in the shoot dry matter indicated K deficiency. With crop residues considerable amounts of K (15 kg t^{-1}) were provided and raised the K concentrations in the plants to the sufficiency range. Although with crop residues some P was provided (1.5 kg t^{-1}), the beneficial effects were primarily attributed to increased P acquisition by the millet plants, which was reflected in enhanced root growth in the topsoil (0–10 cm).

Key words: Crop residue; Pearl millet; *Pennisetum*; Phosphorus; Root growth; West Africa

1. Introduction

Traditionally, soil fertility in West Africa has been maintained through shifting cultivation (Matlon, 1985). In recent decades more marginal land with low fertility has been taken under cultivation and the length of fallow periods decreased. As a consequence, crop yield per hectare has decreased (Vierich and Stoop, 1990).

The fertility of the acid sandy soils in the Sahel zone mainly depends on phosphorus (P) availability and organic matter content (Bationo and Mokwunye, 1991b). Phosphorus appears to be the most limiting nutrient for millet growth in these areas (Bationo et al., 1990; Payne et al., 1991) where the crop does not respond to nitrogen (N) fertilizer until the P demand is met (Bationo et al., 1986). Although due to the low

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SSDI 0378-4290(94)00004-V

P sorption capacities of these soils (Mokwunye et al., 1986) already low levels of P fertilizer significantly increase crop yields (Bationo and Mokwunye, 1991a), the use of P fertilizer for pearl millet is hardly feasible for low-income local farmers.

Application of organic materials, particularly in combination with mineral fertilizers, may maintain a relatively high production level (Pichot et al., 1974; Vlek, 1990). However, the availability of organic materials, such as manure or crop residues, is limited. The application of manure is often restricted to areas in the immediate neighbourhood of villages. On the other hand, the availability of crop residues (millet straw) is limited since they are used as building material, fuel (Nicou and Charreau, 1985), and fodder during the dry season.

Previous studies (Bationo et al., 1987; Hafner et al., 1993a), showed that annual application of crop residues as surface mulch over a 5-year period steeply increased biomass of millet production. This enhancement has been attributed to the improvement of P nutrition by both increased P mobility in the soil due to chelation of Al and Fe, and increased P acquisition by stimulation of root growth (Kretzschmar et al., 1991). The stimulation of root growth was attributed to phytohormone production by soil microorganisms (Kretzschmar et al., 1991; Hafner et al., 1993b). Annual application of crop residues also increased the soil pH, the contents of exchangeable cations (K, Ca, Mg) and the base saturation (Kretzschmar et al., 1991; Geiger et al., 1992). These effects were attributed to the recycling of mineral nutrients and the entrapment of fertile eolian materials (Geiger et al., 1992).

It was the objective of this study to test whether the benefical effects of crop residues can be achieved in the first year or require long-term application, and whether the efficiency can be increased by the mode of application.

2. Material and methods

Two field experiments were conducted during the rainy seasons of 1990 and 1991 at the ICRISAT Sahelian Center (ISC) located at Sadoré, 45 km southeast of Niamey, Niger, West Africa (13°15′N latitude, 2°18′E longitude). Mean annual rainfall is 560 mm with a 25% probability of receiving less than 441 mm (Sivakumar, 1986), and 36°C average daily maximum temperature on a yearly basis.

The soils at the experimental site are derived from eolian sand deposits and are representative of those used for pearl millet production in the area. The soil is classified as a Luvic Arenosol (Hebel and Stahr, 1991) or a Psammentic Paleustalf: sandy, siliceous, isohyperthermic (US-Soil Taxonomy; West et al., 1984). The topsoil properties are as follows: sand, 91%; clay, 5.3%; pH (H_2O; 1:1), 4.9; CEC, 1.3 meq 100 g^{-1}; base saturation, 42%; exchangeable K, 0.4 meq kg^{-1}; organic carbon, 0.17%; total N, 190 mg kg^{-1}; total P, 73 mg kg^{-1}; available P (Bray I), 2.6 mg kg^{-1}.

In Experiment I the effects of long-term (since 1986) and short-term (since 1990) application of crop residues (Experiment Ia) at different amounts and modes, and of phosphorus fertilization (Experiment Ib), on dry matter yield of pearl millet were studied.

In Experiment II the role of K in the growth enhancement by crop residues was evaluated.

Experiments Ia and Ib were carried out during 1990 and 1991 on a field that had been cultivated continuously with millet since 1980. Until 1986 no fertilizers had been applied and all crop residues had been removed after harvest. During the cropping seasons of 1986, 1987, 1988 and 1989, P fertilizer and crop residues have been applied in various combinations. Treatments were arranged with six replications in a split-plot design with an individual plot size of 12×12 m. The main-factors were: crop residues removed after harvest (−CR) and crop residues (2 t ha^{-1}) left on the field as mulch (+CR); the sub-factors were: no P fertilizer (−P) and application of P fertilizer (+P; 13 kg P ha^{-1}) as single superphosphate (SSP).

At the end of the 1989 growing season all plots (−CR; +CR; −P; +P) were divided into six subplots to study in the following seasons the effects on dry matter production of different rates and forms of applied crop residues in combination with P.

In Experiments Ia and Ib crop residues from adjacent sites were applied at the end of the previous cropping season (October) and remained on the soil surface during the following dry season. At the beginning of the cropping seasons 1990 and 1991 crop residues were either incorporated by ploughing (incorporated) to a depth of about 20 cm, burned on the plots (ash) or remained on the surface as mulch (mulch). Crop residues were applied at rates of 2 and 6 t ha^{-1}, and P was applied as single superphosphate at a rate of 13 kg ha^{-1} as before.

In order to study long-term and short-term effects of crop residues the experiments were conducted on plots which either had received crop residues since 1986, or in 1990 for the first time. The residual effect of the long-term crop residue application was studied by omitting crop residue (− CR) application in 1990 and 1991 on plots which had received crop residues since 1986.

Experiment II was conducted in 1991 on plots with long-term crop residue application (+ CR since 1986) and with short-term crop residue application (+ CR since 1991).

In this experiment, particular emphasis was put on evaluation of the role of potassium (K) in the growth enhancement by crop residue application. Accordingly, K as KCl was supplied as mineral fertilizer at a level equivalent to that applied with 2 t crop residues ha^{-1}, namely 30 kg K ha^{-1}.

In contrast to Experiment I, crop residues were applied at the end of the dry season (May) of 1990/1991.

The experimental setup of Experiments Ia, Ib and II is summarized in Table 1.

Both P and K were applied broadcast after the crop residues had been applied (mulch, ash, incorporated) but prior to sowing. Nitrogen was applied in both experiments as calcium ammonium nitrate (CAN) and split into two doses of 15 kg N ha^{-1} each at the five-leaf stage (20 days after sowing; DAS) and at tillering (40 DAS).

Table 1
Experimental set up

	Treatment history (1986–1989)	Treatments in 1990 and 1991	
		Crop residues	Mineral fertilizer
Exp. Ia	−CR	−CR	−P and/or +P
	−CR	+CR[a]	−P and/or +P
	+CR[a]	+CR[a]	−P and/or +P
	+CR[a]	−CR	−P and/or +P
Exp. Ib	−CR	−CR	−P and/or +P
	+CR[a]	+CR[b]	−P and/or +P
Exp. II	−CR	−CR	−K and/or +K
	−CR	+CR[a]	−K and/or +K
	+CR[a]	+CR[a]	−K and/or +K
	+CR[a]	−CR	−K and/or +K

[a] 2 t millet straw ha^{-1}; applied as mulch.
[b] 2 t or 6 t millet straw ha^{-1}; applied as ash, mulch or incorporated.

Pearl millet [*Pennisetum glaucum* (L.) R. Br., cv. CIVT] was sown manually in "pockets" at 1 × 1 m spacing. At the five-leaf stage (20 DAS) the stand was thinned to three plants per m^{-1}. Weeding when necessary was performed with hand-hoes.

For determination of dry matter accumulation in both experiments, plants of a 12-m^2 area were harvested at tillering (40 DAS) and at maturity (100 DAS) and divided into shoots, panicles and seeds. The plant material was dried at 65°C to constant weight.

At tillering, for studies on root growth, auger samples of soils were taken at a distance of 50 cm from the plants and in a soil depth of 0–10 and 10–30 cm. Roots were separated from soil by carefully washing over a 0.75-mm sieve. Root length was determined using the line intersection method of Tennant (1975).

Nitrogen (N) concentrations in shoots and seeds were determined using a Macro-N-Analyzer (Heraeus). For analysis of P, K, calcium (Ca), magnesium (Mg), zinc (Zn), aluminium (Al) and manganese (Mn), plant material was dry ashed at 450°C and ash dissolved in 1:30 (*v*/*v*) diluted HNO_3. Magnesium, Zn, Al and Mn were determined by atomic absorption spectrophotometry (Philips Pu 9400 X), K and Ca by flame photometry (Eppendorf, Elex 6361), and P colorimetrically by using the vanado-molybdate method (Gericke and Kurmies, 1952).

3. Results

3.1. *Experiment Ia and Ib*

In 1990 and 1991 highest total dry matter at maturity (Table 2) was achieved following long-term application of 2 t crop residues ha^{-1} yr^{-1} as mulch (+ CR since 1986). When crop residue application was omitted (− CR since 1990), total dry matter yield decreased greatly, in the first year (1990), and in the second year (1991) approached levels similar to that obtained on plots which had never received crop residues (− CR since 1986). This indicates the relatively small residual effect of crop residues even after long-term application.

In contrast, short-term application of crop residues (+ CR since 1990) doubled total dry matter yield in

Table 2
Short-term and long-term effects of crop residue application (+ CR) and phosphorus fertilization (+ P) on total dry matter yield of pearl millet at maturity (Sadoré, rainy season 1990 and 1991)

Pretreatment	Treatment	Total dry matter yield (kg ha^{-1})	
		−P	+P
Since 1986	1990	1990	
−CR	−CR	644	1164
−CR	+CR	1041	2356
+CR	+CR	1878	3520
+CR	−CR	876	1622
	SE	184	312
	CV (%)	81	71
Since 1986	1990 + 1991	1991	
−CR	−CR	95	985
−CR	+CR	798	1353
+CR	+CR	1371	2720
+CR	−CR	162	1032
	SE	152	256
	CV (%)	122	83

the first year (1990) and increased it by a factor of 8 in the second year (1991).

The decline in total dry matter with omission of crop residues was generally more distinct than its increase following the initial application.

In all treatments, dry matter yield was increased by P fertilizer, and the effects of crop residues followed the same pattern as without P (Table 2). However, the decline in dry matter yield was not as pronounced when crop residue application was omitted.

In 1990, short-term application of crop residues (− P; + CR since 1990) and + P only (+ P; − CR since 1986) gave similar dry matter yields. In both years maximum total dry matter and grain yield were achieved with long-term + CR combined with + P.

In the shoot dry matter at tillering, the mineral elemental concentrations (Table 3) of N, Ca, Mg, and Zn were generally in the sufficiency range, and were highest in long-term crop residue application (+ CR since 1986). Short-term crop residue application (+ CR since 1990) increased the concentrations of these nutrients and, except for N, they decreased when the application of crop residues was omitted (− CR since 1990).

The concentrations of Mn and Al in the shoot dry matter were high and not significantly affected by CR (Table 3).

In the treatments without crop residues, both long-term (since 1986) and short-term (since 1990), the concentrations of K and P were in the deficiency

Short-term (+ CR since 1990), but especially long-term application of crop residues (+ CR since 1986) increased the concentrations of K to the sufficiency range, whereas the concentrations of P could be increased only by long-term application of crop residues (+ CR since 1986). Even with long-term application of crop residues the P concentrations remained in the suboptimal range, mainly due to dilution of the P concentrations by growth (Table 3).

Root growth, expressed by the root-length density, was distinctly affected by crop residues (Table 4). At tillering, root-length density between pockets was highest in the topsoil (0–10 cm) and greatest with long-term application of crop residues (since 1986). The same was true for P uptake (Table 4). In accordance with the response in total dry matter yield (Table 2), the decrease of root growth and P uptake was more distinct when the application of crop residues was omitted (− CR since 1990) compared to the application of crop residues for the first

The enhancement effect of crop residues on P uptake observed at tillering continued until maturity. Without P fertilizer in 1990, total P uptake ranged between 0.5 and 1.7 kg P ha^{-1}, whereas with P fertilizer it increased up to 5.0 kg P ha^{-1} (Table 4). In comparison, P supply with mineral fertilizer was 13 kg ha^{-1} and with crop residues about 1 kg ha^{-1}.

In 1990 and 1991 total dry matter at maturity (Fig. 1) was lowest without crop residues (− CR) and P (− P), and increased steeply by crop residue application depending on the mode and dose of application. When applied as mulch the effect of 2 t crop residues ha^{-1} on total dry matter yield was similar to that of 6 t crop residues ha^{-1}. With respect to dry matter production, ash application was similar to mulch application in 1990, but was not effective in 1991. This may have been caused by leaching of nutrients, since percipitation in 1991 (603 mm) was much higher than in 1990 (400 mm). In both years highest dry matter yield was achieved by incorporation of crop residues.

Again, the total dry matter yield was higher with P fertilization (+ P), but the relative effects of mode and dose of crop residues were similar to those at − P.

Table 3
Short- and long-term effects of crop residue application (+ CR) without phosphorus fertilization (− P) on shoot growth and mineral elemental concentrations in the shoot dry mass of pearl millet at tillering (40 DAS) compared with sufficiency and toxic ranges (Sadoré, rainy season 1990)

Pretreatment since 1986	Treatment 1990	Shoot dry mass (kg ha^{-1})	N (mg g^{-1})	P (mg g^{-1})	K (mg g^{-1})	Ca (mg g^{-1})	Mg (mg g^{-1})	Zn (µg g^{-1})	Al (µg g^{-1})	Mn (µg g^{-1})
−CR	−CR	64	29.9	2.2	17.0	4.4	2.6	20	820	280
−CR	+CR	147	34.3	2.4	28.3	5.3	3.4	n.d.	n.d.	n.d.
+CR	+CR	254	31.3	3.1	41.6	5.6	3.5	23	811	207
+CR	−CR	54	37.5	2.5	21.4	5.4	3.1	n.d.	n.d.	n.d.
	SE	24	1.5	0.1	2.4	0.3	0.2	1	65	23
	CV (%)	91	15.7	18.7	39.9	21.4	25.9	11	25	30
	Sufficiency range		28–35	3–6	30–45	4–9	1–4	17	–	40–150
	Toxic range		–	–	–	–	–	–	>600	–
	References		a	b	b	c	d	e	f,g	b

[a] Dey et al. (1980); [b] Lockman (1972): values refer to grain sorghum; [c] Lanyon et al. (1977); [d] Cummins and Perkins (1974); [e] Gupta et al. (1981); [f] Scott-Wendt et al. (1988); [g] Kretzschmar et al. (1991).

Table 4
Root length density and total P uptake of pearl millet as affected by short- and long-term crop residue application (+ CR)[a] and P fertilization (+ P)[b] (Sadoré, rainy season 1990)

Pretreatment since 1986	Treatment 1990	Root length density (cm cm^{-3})				Total P uptake (kg ha^{-1})			
		Tillering				Tillering		Maturity	
		−P		+P		−P	+P	−P	+P
		0–10	10–30	0–10	10–30 cm				
−CR	−CR	0.9	0.2	2.6	0.4	0.1	0.7	0.6	1.4
−CR	+CR	1.0	0.2	1.7	0.4	0.4	0.5	0.9	2.7
+CR	+CR	1.6	0.4	2.8	0.8	0.8	0.5	1.7	5.0
+CR	−CR	1.1	0.5	1.2	0.2	0.1	0.7	0.9	2.0
	SE	0.1	0.1	0.3	0.1	0.1	0.1	0.1	0.4
	CV (%)	51.8	74.2	61.2	82.6	88.9	23.6	53.8	50.4

[a] +CR = 2 t CR ha^{-1}.
[b] +P = 13 kg P ha^{-1} (P as SSP).

The application of the various forms and levels of crop residues increased the concentrations of Ca and Mg in the shoot dry matter at tillering from 4.4 (without crop residues) to 5.7 mg Ca g^{-1} dry matter (2 t crop residues; incorporated) and from 2.6 to 4.1 mg Mg g^{-1} dry matter (Rebafka, 1993).

Crop residues increased the concentrations of K in the shoot dry matter to the sufficiency range at tillering (Table 3) and to high values at maturity, irrespective of the level and mode of application (Table 5). However, due to differences in dry matter production and to luxury K accumulation (6 t crop residues; incorporated) the total K uptake differed by a factor of up to 25.

Without mineral fertilizer P, the concentrations of P in the shoot dry matter at tillering were in the deficiency range in the treatment without crop residues (− CR) (Table 6) and increased to the suboptimal range by application of crop residues.

With application of mineral P, the K concentrations in the shoot dry matter were only slightly increased both at tillering and maturity. In contrast to the shoot concentrations, the total uptake of P was increased several fold by either crop residues or mineral fertilizer P

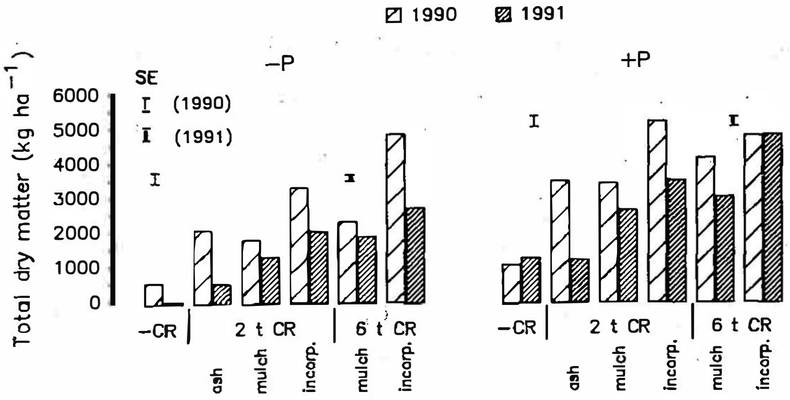

Fig. 1. Effect of long-term crop residue (CR) and phosphorus fertilizer (+P) application on total dry matter yield of pearl millet at maturity. On all plots crop residues had been applied between 1986 and 1989 at a rate of 2 t ha^{-1} as mulch. In the growing seasons 1990 and 1991 crop residues were either omitted (−CR), burned (ash), mulched (mulch) or incorporated (incorp.) at rates of 2 and 6 t ha^{-1}. Vertical bars are standard errors of means (SE).

Table 5

Potassium concentrations in the shoot dry matter and total uptake of potassium in the shoots and grains of millet at tillering (40 DAS) and at maturity (100 DAS) as affected by different rates and modes of applied crop residues (CR) (Sadoré, rainy season 1990)

	Tillering	Maturity		
	Shoots	Shoots[a]	Grains	Total[b]
	K conc. (mg g^{-1})			
−CR (since 1986)	17.0	2.9	3.7	
+CR (since 1986)				
2t ha^{-1}; ash	33.8	9.4	3.8	
2t ha^{-1}; mulch	41.6	9.0	3.6	
2t ha^{-1}; incorp.	38.3	9.5	3.7	
6t ha^{-1}; mulch	42.6	12.8	3.9	
6t ha^{-1}; incorp.	42.7	13.6	4.2	
SE	2.5	1.0	0.1	
CV (%)	29.3	46.3	10.0	
	K uptake (kg ha^{-1})			
−CR (since 1986)	1.1	1.6	0.4	2.0
+CR (since 1986)				
2t ha^{-1}; ash	5.7	14.1	2.5	16.6
2t ha^{-1}; mulch	10.6	13.8	1.2	15.0
2t ha^{-1}; incorp.	22.3	23.8	3.3	27.1
6t ha^{-1}; mulch	6.2	23.0	2.3	25.3
6t ha^{-1}; incorp.	27.8	51.5	4.7	56.2
SE	2.1	3.8	0.4	4.0
CV (%)	75.2	89.2	63.9	83.7

[a] Sufficiency concentrations of K in shoots: 15 mg g^{-1} dry mass (Pieri, 1982).
[b] Excluding roots.

(Table 6), indicating that the lack of or the small treatment effects on the P concentrations in the shoots were mainly caused by differences in dilution by growth.

At both levels of crop residues (2 and 6 t ha^{-1}) P uptake was much more increased by incorporation of crop residues than by application as mulch (Table 6).

Especially without P fertilizer, uptake of P at tillering (Table 6) corresponded well with root-length density

Table 6

Phosphorus concentrations in the shoot and grain dry matter and total uptake of P in the shoots and grains of millet at tillering (40 DAS) and at maturity (100 DAS) as affected by different rates and modes of crop residue application (CR) and P fertilizer (Sadoré, rainy season 1990)

	P content (mg g^{-1})			P uptake (kg ha^{-1})			
	Tillering	Maturity		Tillering	Maturity		
	Shoots	Shoots	Grains	Shoots	Shoots	Grains	Total
without P fertilizer							
−Cr (since 1986)	2.2	0.5	2.7	0.1	0.3	0.3	0.6
+CR (since 1986)							
2t ha^{-1}; ash	3.2	0.4	3.0	0.5	0.6	2.0	2.6
2t ha^{-1}; mulch	3.1	0.5	3.1	0.8	0.7	1.0	1.7
2t ha^{-1}; incorp.	2.6	0.4	3.1	1.5	1.1	2.7	3.8
6t ha^{-1}; mulch	2.8	0.6	3.2	0.4	1.1	1.8	2.9
6t ha^{-1}; incorp.	2.5	0.9	3.5	1.6	3.5	3.9	7.4
SE	0.1	0.1	0.1	0.1	0.3	0.3	0.5
CV (%)	20.2	49.1	15.3	69.7	118.6	68.5	80.6
with P fertilizer (13 kg P ha^{-1})							
−CR (since 1986)	2.8	0.6	3.0	0.7	0.5	0.9	1.4
+CR (since 1986)							
2t ha^{-1}; ash	3.0	0.5	3.4	0.6	1.3	3.3	4.6
2t ha^{-1}; mulch	2.5	0.9	3.5	0.5	2.4	2.6	5.0
2t ha^{-1}; incorp.	2.6	0.5	3.7	1.9	1.9	4.9	6.8
6t ha^{-1}; mulch	3.3	0.8	3.3	1.2	2.5	3.7	6.2
6t ha^{-1}; incorp.	2.8	1.0	3.7	2.9	3.8	3.6	7.4
SE	0.1	0.1	0.1	0.2	0.2	0.3	0.5
CV (%)	12.6	42.1	9.7	69.5	66.3	37.6	42.1

Table 7

Root length density (cm cm^{-3}) in the top soil (0–10; 10–30 cm) at tillering as affected by the rate and the form of applied crop residue (+CR) and P fertilizer (13 kg P ha^{-1}) (Sadoré, rainy season 1990)

Treatments	−P fertilizer		+P fertilizer	
	0–10 cm	10–30 cm	0–10 cm	10–30 cm
−CR (since 1986)	0.9	0.2	2.6	0.4
+CR (since 1986)				
2t ha^{-1}; ash	0.9	0.2	2.0	0.4
2t ha^{-1}; mulch	1.6	0.4	2.8	0.8
2t ha^{-1}; incorp.	3.6	0.8	3.6	1.2
6t ha^{-1}; mulch	1.6	1.0	1.9	0.4
6t ha^{-1}; incorp.	2.8	0.8	3.2	0.9
SE	0.3	0.1	0.2	0.1
CV (%)	90.6	101.8	50.2	87.9

in the top soil (0–10 cm) (Table 7), with the exception of ash application which increased P uptake five-fold but did not enhance root growth. Root length densities decreased sharply with soil depth (10–30 cm) and treatment effects became less clear.

3.2. Experiment II

Since deficiency

factors responsible for poor millet growth (Table 3), another experiment was conducted in 1991 comparing the effect of 30 kg K ha^{-1} (+K), which was equivalent to the amount applied with 2 t crop residues ha^{-1}, with that of crop residues on dry matter yield (Fig. 2).

Again, total dry matter yield at maturity (Fig. 2) was reduced distinctly without crop residues (−CR) on plots with a long-term crop residue history (+CR since 1986), but increased by crop residues either as mulch or ash, even when applied for the first time (+CR since 1991). The supply of mineral K was less effective in increasing dry matter yield than crop residues as mulch or ash.

The K concentrations in the shoot dry matter were lowest in the treatments without crop residue (−CR) and increased in the first year to similar levels by application of either mineral fertilizer or crop residues as mulch or ash (Fig. 2). In the long-term application of crop residues (+CR since 1986), the K concentrations were generally higher, particularly with application of mineral K. A comparison of the treatment effects on K concentrations and total dry matter yield indicates that yield increase by crop residues can be explained only in part by improvement of the K nutritional status.

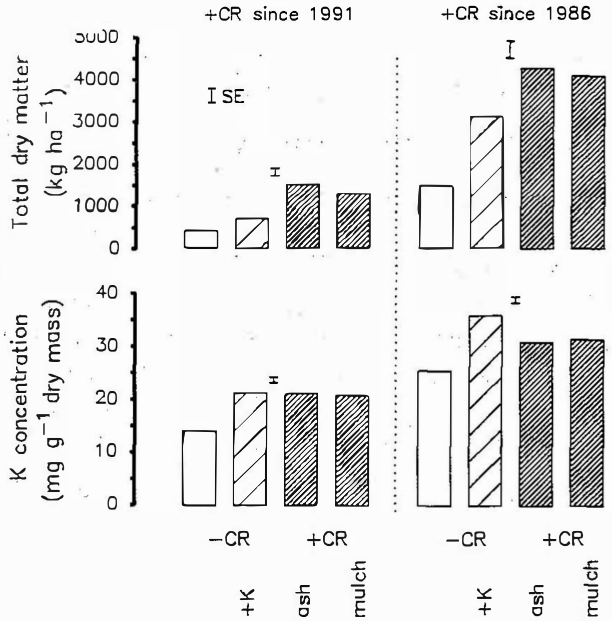

Fig. 2. Effect of short-term (+CR since 1991) and long-term (+CR since 1986) crop residue application (+CR) and of equivalent amounts of K as mineral fertilizer (+K) on total dry matter yield at maturity and on K concentrations in the shoot dry matter at tillering. Vertical bars are standard errors of means (SE) (Sadoré, rainy season 1991).

4. Discussion

The drastic decrease in total dry matter (Table 2) in the first year of omitting crop residue application emphasizes that productivity of millet on these soils is dependent on the annual addition of crop residues. For maintenance of soil fertility, the return of crop residues to the fields

et al., 1981; Dugue, 1985). The availability of crop residues for this purpose is however limited since they are used for building, as fuel, and for animal feeding (Nicou and Charreau, 1985). The observation that soil fertility decreases with the distance between the villages and fields (Bationo and

rectly indicates the limitation of crop residues for fertilization of distant fields and the impact of intensive nutrient recycling around places where humans and animals are concentrated.

The enhancement effect of crop residues on crop productivity depends on their management after harvest. Burning increased both the contents of exchangeable K and soil pH (Hebel and Stahr, 1991), resulting in improved K nutrition (Table 5) and increased P uptake (Table 6) due to improved P availability (Nguu, 1987). However, burning also results in a considerable loss of carbon, nitrogen and sulfur (Charreau and Poulain, 1964). Nevertheless, in Niger burning of crop residues on the fields

tice for weed control and elimination of insects and diseases inherent in the straw (Bationo and Mokwunye, 1991b).

Besides the main effect attributable to the improvement of nutrient supply, crop residues have other benefits, including reduction of wind and water erosion, protection of seedlings from sandblast, control of soil temperature (Lal, 1986; Fortin and Pierce, 1990) and water conservation (Papendick and Parr, 1989). The last two factors are less important at this site (Bley, 1990).

With respect to dry matter production and efficiency per unit straw dry weight, the incorporation of crop residues proved to be better than ash or mulch application (Fig. 1). Against expectations (Ganry et al., 1978; Bationo and Mokwunye, 1991b), the incorporation of crop residues with their typical high C : N ratio (100 : 1) did not adversely affect early growth of millet by inducing N deficiency. It is more likely that incorporation of crop residues improved microbial activity and rate of straw decomposition, reduced soil bulk density (ICRISAT, 1986) thus promoting root proliferation and penetration (Fussell et al., 1987), and improved water conservation and infiltration, as is also achieved by ridge cropping (Hulugalle, 1987). Since total N in these soils is very low (0.02%), it is unlikely that the effect of incorporation on dry matter yield is to be attributed to mineralization of soil N. In Niger, soil tillage without crop residue incorporation failed to increase yields significantly (Christianson et al., 1990).

The enhancement of dry matter yield by use of crop residues was mainly related to the improvement of the K and P nutrition of millet (Tables 3, 5, 6), by nutrient recycling (K) and improved nutrient acquisition (P), although the entrapment of fertile eolian material as a contributing factor (Geiger et al., 1992) can not be excluded and may be significant, especially for K. Studies of Drees et al. (1990) show that transported input of K via eolian dust collected in Niger was about 2 kg ha^{-1} yr^{-1} and thus in the same range but still too low to explain the additional K uptake of millet of about 9 kg ha^{-1} yr^{-1} following short-term crop residue application.

Permanent millet production on these sandy soils without returning crop residues leads to a rapid depletion of nutrients, especially of K (Pieri, 1985; De Ridder and van Keulen, 1990). Since in the above-ground biomass the largest proportion of K, Ca and Mg remains in the straw, crop residue application is a component of soil fertility maintainence (Lal, 1990) and the recycling of mineral nutrients, K in particular. The higher concentrations of K, Ca and Mg in the shoots of millet following crop residue application (Table 3) are presumably caused by the additional K, Ca and Mg supplied with the millet straw (containing in kg t^{-1}: 15 K, 4 Ca, 3 Mg).

It is evident that in millet, K deficiency is one of the factors responsible for poor growth (Scott-Wendt et al., 1988), especially without crop residue application (Hafner et al., 1993a). The application of mineral K (30 kg ha^{-1}), equivalent to 2 t ha^{-1} millet straw, prevented the drastic yield decline which occurred when crop residue application was omitted, but it was only half as effective as mulch application (Fig. 2). However, in view of the very low levels of exchangeable K in these soils (Scott-Wendt et al., 1988), for maintenance of soil fertility in the long run it is advisable to supply K with fertilizer, especially for intensive millet production (Pieri, 1982).

Since P is the most growth-limiting nutrient for millet in these soils (Bationo et al., 1990), the higher yield efficiency of crop residues compared to mineral K fertilizer (Fig. 2) was presumably related to improved P nutrition. The growth enhancement effect of crop residues was related to increased P uptake (Tables 4 and 6). Since the extent of root surface is important for P acquisition in general (Jungk and Claassen, 1989), and root mass in the topsoil is highly correlated with P uptake in millet in particular (Kapur and Sekhon, 1985), the promotion of root growth (Tables 4 and 7) most probably contributed substantially to the effect of crop residues on P nutrition and growth.

Tropical grasses such as sorghum (Sarig et al., 1990) and pearl millet (Wani et al., 1988) are known for their rhizosphere association with N_2-fixing bacteria (e.g. *Azospirillum*) which are able to produce phytohormones (auxin) resulting in a promotion of root growth (Joshi and Rao, 1989; Martin et al., 1989). The assumption that crop residue application stimulates microbial activity in the rhizosphere of millet is supported by results obtained in a field experiment at an adjacent site, where crop residues applied as mulch increased the number of N_2-fixing and total bacteria in the rhizosphere of millet (Hafner et al., 1993b).

Since the activity of phytohormone-producing diazotrophic bacteria in the rhizosphere is enhanced by additional supply of carbon sources with a high C : N ratio (Alexander and Zuberer, 1988; Martin et al., 1989), crop residues stimulated root growth only when applied as mulch or when incorporated, but not when burned (Table 7).

The ability of some bacteria to solubilize organic P compounds (Bajpai and Rao, 1971) is probably of minor importance because the content of organically bound P in this soil is low (Bationo and Mukwunye, 1991a).

Application of crop residues only slightly increased the extractable P (Bray-P) in these soils (Kretzschmar et al., 1991; Geiger et al., 1992; Hafner et al., 1993a).

Although the additional P supply via crop residues was supposed not to be of major importance for the higher P uptake (Hafner et al., 1993a), this contribution cannot be ignored. At least the increase in total P uptake of millet when supplied with crop residues was similar to the amount of P applied with crop residues (Table 4).

Application of crop residues in combination with mineral P increased the utilization of fertilizer P, if the ''difference method'' is used: without crop residue application (since 1986) the utilization of fertilizer P was about 6% and increased to 14% when crop residues were applied for the first [illegible] Table 4). Highest utilization of fertilizer P (25%) was found with long-term crop residue application. The improvement of uptake and utilization of fertilizer P by crop residue application can be attributed to both an increase in root-length density (Table 7) and to mobility and influx of P per unit root length (Hafner et al., 1993a).

5. Acknowledgement

The authors thank Miss G. Follner for technical assistance, ICRISAT for providing the research infrastructure and the Deutsche Forschungsgemeinschaft (SFB 308) for financial support.

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