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The effect of crop residue and fertilizer use on pearl millet yields in Niger

A. Bationo[1], C.B. Christianson[2] & M.C. Klaij[3]
[1]*IFDC – West Africa, B.P. 4483, Lomé, Togo*; [2]*International Fertilizer Development Center (IFDC), Research and Development Division, P.O. Box 2040, Muscle Shoals, Alabama 35662, USA (corresponding author)*; [3]*ICRISAT, Sahelian Center BP 12404, Niamey, Niger*

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Abstract

A field study was conducted over a 4-year period in Niger, West Africa, to determine the effects of crop residue (CR), fertilizer, or a combination of crop residue and fertilizer (CRF) on yields of pearl millet (*Pennisetum glaucum* [L.] R. Br.). Despite a decline in yields of control plots (initial yields were 280 kg grain ha^{-1} declining to 75 kg grain ha^{-1} over 4 years), yields of fertilizer plots were maintained at 800–1,000 kg grain ha^{-1}. Continued application of CR slowly augmented yields to levels similar to those of the fertilized plots. The effects of CR and fertilizer were approximately additive in the CRF plots. Addition of CR and fertilizer increased soil water use over the control by 57 mm to 268 mm in an average season and helped trap wind-blown soil. These plots tended to exhibit slightly higher soil pH and lower Al saturation than did the fertilized treatments. Return of CR to the soil resulted in significantly reduced export of most plant nutrients, especially Ca, Mg, and K.

Introduction

The climate in the major agricultural zone of Niger is characterized by low rainfall (400–600 mm) that varies greatly in both total amount received and distribution (Sivakumar, 1986). In addition, high evaporative demand and the low native soil fertility limit agricultural production. In this region, pearl millet (*Pennisetum glaucum* [L.] R. Br.) is the most commonly grown cereal, making up to 90% of the cropped area though yields are typically low (270 kg ha^{-1}–IRAT, 1974). Because of the rapidly expanding population in this region, food production must be increased in a sustainable manner to meet the future nutritional requirements of the people (Pieri, 1986). Though a significant increase in total production can be achieved through expansion of current agricultural practices into marginal areas, the bulk of the additional production must be the result of higher yields on existing farms. Techniques developed to achieve this goal must be adapted to the very limited resource base of the average farmer if they are to have a significant impact on total food production. Within this constraint, fertilizers have a significant role to play (IRAT, 1975); moreover, in recent reviews, Fussell *et al.* (1987, 1989) conclude that soil fertility is the principal limitation to improving crop yields for millet–based cropping systems.

Phosphorus is often observed as being the nutrient most severely limiting yield in this region (Pichot *et al.*, 1979), though these needs can be met by relatively low rates of fertilizer. In the presence of adequate P, however, a significant response to N is found only in years of adequate rainfall (Christianson *et al.*, 1990; Pieri, 1973). Yield response to K is generally weak though its use may improve the vigor of young plants (Pieri, 1986).

Traditionally, soil fertility in West Africa has been maintained through shifting cultivation where farmers abandoned land to fallow as productivity declined. Typically, a period of at least 7 years was required for land to be returned to initial fertility levels (Charreau, 1972), but increasing population pressure has shortened the fallow period in many areas.

Despite generally low nutrient levels in Sahelian soils, millet roots explore a large volume of soil and are thus able to concentrate significant amounts of nutrients in the plant tissue. The total amount of N and P in the millet plant is apportioned approximately equally among the grain and stover fractions. However, most of the K (92%), Ca (97%), Mg (90%), and S (75%) remain in the stover after harvest (Balasubramanian and Nnadi, 1980) and represent a significant nutrient reserve for the subsequent crop if the stover is returned to the soil. Conversely, removal of this dry matter can result in rapid physical and chemical degradation of the soil and consequent depression of yields (Pichot *et al.*, 1981). Use of mineral fertilizer can extend soil productivity for a significant period even if residues are removed though yields will ultimately be expected to decline as micronutrient levels become depleted. The return of crop residues can delay this soil degradation and thus result in more stable cereal production.

Studies of millet production have shown a significant correlation between stover removal and declining grain yields due to the associated nutrient loss. On the other hand, straw decomposition is very rapid in this region and, in the absence of mineral fertilizer, incorporation of millet compost was shown to decrease soil organic carbon levels by stimulating mineralization of native organic matter (Feller and Ganry, 1982). In addition, straw tends to be relatively deficient in N, and therefore its incorporation into the soil can significantly depress millet yields due to immobilization of soil N (Ganry *et al.*, 1978; Traoré, 1974).

Traditionally, very little stover has been used in maintenance of soil fertility in the Sahel. The problem is not one of stover quality but rather its availability (Allard *et al.*, 1983; Pieri, 1985). Trees are generally not plentiful, and straw is used as fuel and building material as well as a source of animal feed. Though some of the nutrients will be returned to the soil as manure and thus remain in the fields when the stover is consumed as feed (Quilfen and Milleville, 1983), animals tend to be kept near the village. As a result, soil fertility tends to decline as distance from the village increases (Balasubramanian and Nnadi, 1980). Also, straw used as fuel is burned in the village, and any ash that is put back into the soil is generally placed in those fields closest to the village.

The objective of this experiment was to assess the effects of fertilizer use and crop residue management on the production of millet in Niger.

Materials and methods

Site description

A field study was initiated in 1983 at Sadore, 40 km SE of Niamey, Niger, at the site of the Sahelian Center of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). The soils of the experimental site are derived from eolian sand deposits, and the 0- to 15-cm soil layer has 940 g kg^{-1} sand and 30 g kg^{-1} clay with a CEC of 0.9–1.0 cmol(+) kg^{-1} and organic matter content of 2.0 g kg^{-1}. As measured with a rain simulator, water infiltration rates are in excess of 100 mm hr^{-1} and a rapid hydraulic conductivity assures a quick return to field capacity after a rainfall event. Soil water at field capacity is 0.09 to 0.10 cm^3 cm^{-3} (Klaij and Vachaud, 1992). By the USDA classification system, the soil is a sandy Psammentic Paleustalf: sandy, siliceous isohyperthermic (West *et al.*, 1984). The long-term annual rainfall in Niamey (the nearest site of long-term data) is 560 mm, and the average temperature is 29°C (Sivakumar, 1986).

Experimental design

The trial was a factorial experiment in a randomized complete block design comparing two levels each of mulching and fertilization in four replicates. Thus, treatments consisted of (1) control (no fertilizer or crop residue); (2) fertilizer only (17 kg P ha^{-1} as single superphosphate, 30 kg N ha^{-1} as urea, and 25 kg K ha^{-1} as KCl); (3) crop residue (CR) only; and (4) the return of crop residue and the use of fertilizer (CRF). Treatments were permanently assigned to plots.

Fertilizers were surface applied and incorporated by tractor-drawn disc and harrow (1983 and 1984) or by hand rake (1985 and 1986). In the first year of the trial, crop residue was applied to the CR and CRF plots 2 weeks before planting: the chopped (15 cm length) millet stover was applied at a rate of 4 tons ha^{-1}. In subsequent years, the stover produced on the plots receiving mulch was returned to that plot and no attempt was made to equalize the total amounts of dry matter applied to each of the plots within a treatment. After grain harvest, stover was left standing until early May when it was cut down and incorporated. In order to simulate the local farmers' practice of residue removal, standing stover was cut down in November and removed from the fertilizer only and control plots.

Individual 5- × 10-m plots were separated by a 1-m alley and were hillplanted to pearl millet (*Pennisetum glaucum* [L.] R. Br. var. CIVT) at 1- × 1-m spacing (10,000 pockets ha^{-1}) with 20–30 seeds per pocket. The millet was thinned to three plants per pocket at 3 weeks after planting. At harvest, an area of 32 m^2 was sampled for grain yield and 10 m^2 was harvested for an estimate of straw production. Yield data are based on samples dried at 60°C. In 1986 soil moisture was measured by the neutron moderation technique with access tubes installed in all plots to a depth of 2.60 m.

Soils were sampled in September 1986 (0-15 cm) and analyzed for Bray P1 (Bray and Kurtz, 1945), organic carbon (Nelson and Sommers, 1982), exchangeable bases (Rhoades, 1982), and pH in 1N KCl (McLean, 1982). Plant samples (grain and stover) harvested in 1985 were analyzed for total N (Buresh *et al.*, 1982) and for total P and cations by the ascorbic acid method (Murphy and Riley, 1962) and atomic absorption, respectively, after digestion as described by Blanchar *et al.* (1965).

Results and discussion

Yield

Rainfall varied greatly over the study period in amount received and distribution (Table 1). A high-deficit rainfall pattern in August 1983 limited yield response of fertilized plots, and a severe drought throughout the 1984 season reduced those yields dramatically. In 1985 and 1986, total rainfall was normal and 17% above normal, respectively, and well distributed.

In all years, a significant yield response was found to both crop residue addition and fertilizer use (Table 2). Over the duration of the study, grain yields in the control plots were low and declined steadily. This indicates that the potential for continuous millet production in these soils is very limited in the absence of amendments such as fertilizer or residue.

The yield response to the fertilizer only treatment was pronounced in all years except 1984. The yields obtained with this treatment were quite constant over the 4 years. Thus as yield levels of the control plots continued to decline, the effectiveness of fertilizer use relative to the

Table 1. Monthly rainfall for study period at experimental site as compared to long-term averages

	Normal[a] (mm)	Sadore (mm)			
		1983	1984	1985	1986
May	35	18	44	0	84
June	75	157	42	75	61
July	141	133	91	136	176
August	191	92	57	257	189
September	89	195	26	91	110
October	16	4	0	1	25
TOTAL	547	599	260	560	657

[a]Based on 74 years of data from Niamey, 40 km northwest of Sadore (Sivakumar, 1986).

Table 2. Effect of crop residue and fertilizer use on pearl millet grain and stover yield

	Grain yield (kg ha^{-1})				Stover yield (kg ha^{-1})			
	1983	1984	1985	1986	1983	1984	1985	1986
1. Control	280	215	160	75	ND[a]	900	1,100	1,030
2. Crop residue (CR)	400	370	770	645	ND	1,175	2,950	2,880
(no fertilizer)	(43)[b]	(70)	(380)	(900)		(30)	(170)	(180)
3. Fertilizer	1,040	460	1,030	815	ND	1,175	3,540	3,420
(no CR)	(270)	(114)	(545)	(1,000)		(30)	(220)	(230)
4. Crop residue plus	1,210	390	1,940	1,530	ND	1,300	6,650	5,690
fertilizer (CRF)	(330)	(80)	(1,110)	(1,940)		(40)	(505)	(450)
$LSD_{0.05}$	260	210	180	200		530	650	870

[a]No data;
[b]Numbers in brackets are percentage yield increase over controls.

control became greater and eventually resulted in a tenfold yield increase over the control.

Though reports exist of initial yield suppression due to N immobilization after addition of CR, no negative effects of crop residue addition were found in this experiment. During the first season in 1983, crop residue improved yields 40% though the yield benefit was significantly weaker than that of fertilizer use. After 1984, however, yield responses to application of crop residue were significantly higher and approached those resulting from fertilizer use.

The highest yields were consistently found in the CRF treatments (except in the drought year of 1984). In this case the effects of CR and fertilizer were approximately additive in the normal rainfall years of 1985 and 1986.

The rather low fertilizer rates selected for this study were based on similar national recommendations. Fertilizer rate trials conducted concurrently with this study (data unpublished) show that these fertilizer rates were sufficient to achieve average yields. Trends in stover production were similar to those found with grain yield though less pronounced (Table 2).

Soil moisture

In 1986, a total of 440 mm of rain, close to the average, was received during the crop cycle. Rain was well distributed, and drought stress did

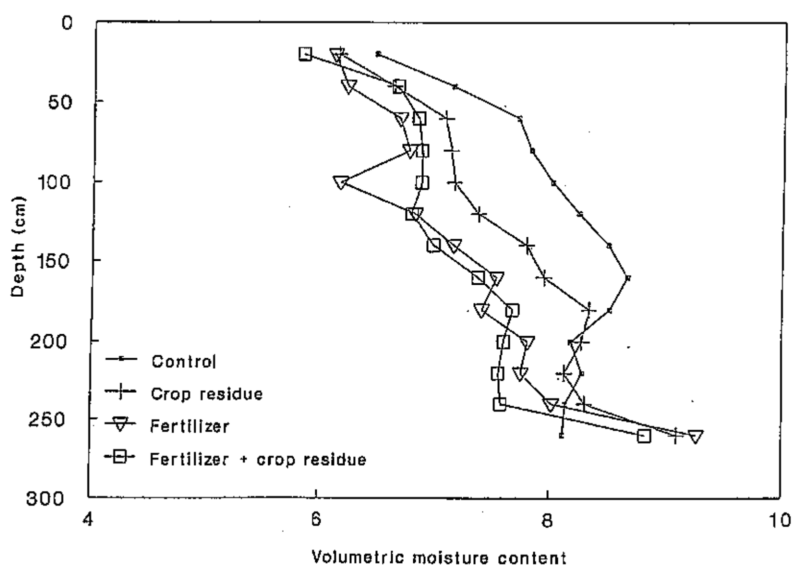

Fig. 1. Distribution of soil moisture within the profile at the end of the 1986 season. Differences between treatments are not significant.

not occur in any of the treatments. The amount of water held in the 0.3–1.4 m profile at harvest was highest at 86 mm for the control treatment and ranged between 74 mm and 78 mm for the improved treatments, the differences not being significant.

However, in a parallel experiment, due to much more frequent soil water measurements, the seasonal water balance could be calculated during the 1986 season using a method described by Klaij and Vachaud (1992). Two treatments identical to the control and CRF plots were evaluated in a quite similar soil. Seasonal water use increased by 57 mm from 211 mm in control plots to 268 mm in CRF plots (SE = 22.4) (Fig. 1). Conversely, the calculated drainage at 1.4 m depth, the maximum effective rooting depth in that year, decreased from 207 mm in control plots to 148 mm in CRF plots (SE = 18.3).

The CRF treatment combined a modest increase of total water use with a substantial higher production. Even in the driest year on record, superior yields were obtained from improved treatments, indicating that soil water is not the primary limiting factor, but low soil fertility.

Analysis of crop residue and grain

Tissue analysis was conducted in 1985 in order to determine the rates of nutrient uptake in the grain and stover fractions of each treatment and allow estimation of the amounts of nutrient returned to the soil in the residue (Table 3). The concentrations of Ca, Mg, N, P, and K in the stover and grain generally did not differ greatly among treatments, the exception being K in grain. However, because of the large yield differences between treatments, there were significant differences in the total amount of each nutrient taken up in the grain and stover.

The uptake of K, Ca, and Mg was much higher in the stover than in the grain, whereas uptake of the other nutrients was lower (P) or equivalent (N). When the crop residue was returned to the soil (CR and CRF treatments), the only export that occurred was in the grain fractions. Conversely, in the control and fertilizer only treatments, nutrients in both the grain and stover fractions were exported from the experiment. This resulted in large differences between the plus- and minus-residue treatments in terms of total nutrient removal (Table 4). Calcium removal in the CR treatment was only 0.07 kg ha^{-1} while the fertilizer and control plots annually lost 6.5 and 2.5 kg ha^{-1}, respectively. Similar, though less pronounced, differences were noted between the treatments for Mg. In CRF treatment, nutrients were returned through the crop residue and therefore, on balance, the export of nutrients in this treatment was lower

Table 3. Effect of crop residue and fertilizer use on the nutrient concentration and uptake in millet grain and stover (1985)

	Nitrogen		Phosphorus		Potassium		Calcium		Magnesium	
	C[a]	U[a]	C	U	C	U	C	U	C	U
	(mg g^{-1})	(kg ha^{-1})	(mg g^{-1})	(kg ha^{-1})	(mg g^{-1})	(kg ha^{-1})	($\mu g\ g^{-1}$)	(kg ha^{-1})	($\mu g\ g^{-1}$)	(kg ha^{-1})
Grain										
1. Control	19.5	3.1	2.5	0.40	3.5	0.6	89.4	0.01	1,090	0.17
2. CR	19.9	15.3	2.5	1.93	5.2	4.0	86.5	0.07	1,020	0.79
3. Fertilizer	20.8	21.4	2.4	2.71	6.1	6.3	86.5	0.09	1,040	1.07
4. CR + fertilizer	20.0	38.8	2.6	5.04	6.7	13	86.8	0.17	1,080	2.09
LSD	1.3	6.4	0.3	0.93	0.5	2.3	2.1	0.03	70	0.36
Stover										
1. Control	6.0	6.6	0.51	0.56	13.9	15.3	2,190	2.41	4,380	4.81
2. CR	6.5	19.2	0.43	1.27	16.0	47.2	1,950	5.75	4,060	12.0
3. Fertilizer	5.7	20.2	0.42	1.49	19.1	67.6	1,820	6.44	3,380	12.0
4. CR + fertilizer	6.3	41.9	0.34	2.26	15.4	102.4	1,750	11.64	3,810	25.3
LSD	2.8	15.4	0.26	0.79	9.0	35.3	1,050	4.80	1,530	7.70

[a]C = concentration in tissue; U = total uptake of nutrient in grain or stover [nutrient concentration multipled by crop (stover) yield].

Table 4. Total nutrient export in CR and CRF treatments (export as grain only) or in control and fertilized treatments (in grain plus stover fractions), 1985. Numbers in brackets indicate nutrient balance (fertilizer nutrient applied minus export in grain or grain plus stover)

	Nutrient export (kg ha^{-1})				
	N	P	K	Ca	Mg
Control	10	1	16	2.5	5
	(−10)	(−1)	(−16)		
CR	15	2	4	0.07	0.8
	(−15)	(−2)	(−4)		
Fertilizer	42	4	74	6.5	13
	(−12)	(13)	(−49)		
CR + fertilizer	39	5	13	0.2	12
	(−9)	(12)	(12)		

(K, Ca, and Mg) than or equivalent to (N and P) that of the fertilizer only treatment even though yields were consistently higher with CRF (Table 4).

Soil analysis

The application of SSP over a period of 4 years resulted in an extractable P level (Bray-1P) of 7.1 and 8.1 μg P g^{-1} soil in the fertilized and CRF treatments, respectively (Table 5). No significant difference was found between the control and CR plots (2.6 and 2.9 μg P g^{-1} soil). Previous studies in this region indicate that soils with a Bray-1P level below 3.0 are very responsive to phosphorus (Bationo *et al.*, 1991).

In comparison with the control plots, fertilizer use had no significant effect on soil pH, Al saturation, or soil organic matter levels (Table 5). However, the soils of the plots that received CR had significantly higher pH and percent base saturation and lower aluminium saturation than did the control or fertilizer only treatment. This was probably due to the large amounts of Ca and Mg returned with the residue to the CR and CRF plots and the chelation of Al and Fe by the organic matter fraction (Manu *et al.*, 1988). The higher pH and reduction in Al saturation would have improved the soil environment for root growth and thus improved yields. However, these changes in soil chemistry were found only in the surface 15 cm, and no significant differences between treatments were found at lower depths in later years (Geiger *et al.*, 1988). The CRF soils combined the best characteristics of both the fertilized (high Bray 1P) and CR (high pH, lower Al saturation) treatments and, as a result, showed the best yields.

No significant difference among the treatments was noted in CEC or organic matter content after 4 years of crop production, partly because of the rapid turnover of organic matter that occurs during the rainy season in this climate. In addition, the measured levels of organic matter were at the lower limit of the analytical technique for bulk soil samples. Therefore, due to soil variability, small changes in organic matter status could not be detected (Table 5).

Discussion

The reason for the positive effects of crop residue on millet yield is not clear. Although residue is reported to increase water infiltration rates and reduce runoff losses in other environments, this is not the case in these sandy soils which exhibit little runoff. However, stover

Table 5. Effect of crop residue and fertilizer use on soil characteristics after four cropping

	pH (KCl)	Bray 1P (μg g^{-1} soil)	Organic matter (%)	Cation exchange capacity (meq 100 g^{-1} soil)	Ca plus Mg saturation (%)	Aluminium (meq 100 g^{-1} soil)	Aluminium saturation (%)
Control	4.11	2.60	0.24	1.05	43	0.49	48
Crop residue only (no fertilizer)	4.37	2.97	0.29	1.02	68	0.21	20
Fertilizer only (no crop residue)	4.11	7.10	0.26	1.01	44	0.44	43
Crop residue plus fertilizer	4.42	8.14	0.34	1.16	72	0.18	16
$LSD_{0.05}$	0.14	1.48	0.05	0.19	11	0.11	10

standing over the 7-month dry season did trap significant amounts of wind-blown dust, which may have provided some extra nutrients to the crop and may have been responsible for the slight improvement of the surface soil characteristics that was associated with crop residue use (Geiger *et al.*, 1992). An additional benefit of residue could be the recycling of scarce nutrients (K, Ca, Mg) to the following crop.

The subtle changes in pH and Al saturation that occurred in the CR and CRF plots may have had an effect on seedling vigor and root development (Scott-Wendt *et al.*, 1988) though these differences do not appear to have been sufficiently large to improve yields so greatly. In separate incubation studies, Kretzschmar *et al.* (1991) suggested that the beneficial effects of crop residue in these soils could be attributed to a reduction in formation of Al-P complexes rather than a decline in the direct effect of Al on root growth. Since P is so crucial for crop growth in these soils, higher levels of soil available P would be expected to promote root growth and thereby improve uptake of soil nutrients.

However, despite the fact that CR exhibited a positive effect on yields, many farmers use the bulk of their CR as fuel, animal feed, or housing and fencing material, and little is left to return to the land. Present rates of fertilizer use in the country are very low and average less than 1.0 kg nutrient ha^{-1} (McIntire, 1986). If the farmer can be provided with a source of fertilizer for 1 or 2 years, the increase in stover yield that can be expected with fertilizer use will supply him with enough CR to meet present needs and still leave sufficient straw to improve the productivity of his soil. This experiment provides data to show that without fertilizer or CR, yields will rapidly decline to the point that the farmer must abandon the field to a long-term fallow. However, if a portion of this CR is returned to the land along with fertilizer, the farmer will be able to increase food and stover production in a sustainable manner. An additional benefit of crop residue is that the increased amounts of stover standing in the fields over the hot, dry season will reduce the effects of wind erosion of the soil.

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