Changes in a Sandy Sahelian Soil Following Crop Residue and Fertilizer Additions

S. C. Geiger,* A. Manu, and A. Bationo

ABSTRACT

The use of crop residues as surface mulches has been shown to have a beneficial effect on the growth of pearl millet [*Pennisetum glaucum* (L.) R.Br.] in the Sahelian zone of West Africa. This study was conducted to discern the mechanism(s) responsible for yield increases resulting from crop-residue additions in a field trial located on a sandy soil at the ICRISAT Sahelian Center near Niamey, Niger. Soil chemical and physical properties were examined to a depth of 120 cm after 5 yr of application of millet residue as a surface mulch, P and N fertilizer, or a combination of fertilizer and residue. Annual residue application resulted in a higher exchangeable-base content, lower Al saturation, and slightly higher available-P values than the control. The use of fertilizer resulted in an increase in available P and exchangeable Ca. The combination of residue plus fertilizer resulted in greater enhancement of soil fertility parameters than the use of these inputs alone. Differences in soil chemistry were operative in only the top 20 cm of the soil profile, however, the surfaces of the plots receiving residues were 15 to 20 cm higher than the surfaces of the control and fertilizer-only plots. The surfaces of the residue plots also had lower clay contents than the surface soils in the nonresidue plots. The increase in soil fertility following the application of millet residue as a surface mulch was due to two mechanisms: (i) the recycling of nutrient elements to the soil following termite and microbial decomposition of the residue, and (ii) the entrapment of eolian materials, which generally have better fertility characteristics than the subsoil, or protection of the more fertile surface soil from the erosive effects of the strong winds that are common in the Sahel.

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Published in Soil Sci. Soc. Am. J. 56:172–177 (1992).

MAJOR MILLET-PRODUCING SOILS of the semiarid region of West Africa are characterized by sandy to sandy loam textures, low clay and organic-matter contents resulting in low CEC, low levels of native soil P and relatively low P-sorption capacities. A small percentage of these soils have been found to contain appreciable amounts of exchangeable Al (Manu et al., 1991).

Research to improve the fertility status of these soils includes the use of inorganic fertilizers and organic amendments (manure, crop residues, and household refuse). Phosphorus appears to be the most limiting nutrient to millet growth in the Sahel, where millet does not respond favorably to N fertilizer until the P requirement is first met, at which point a further yield increase might occur with the addition of N (Bationo et al., 1986). The use of manure as a soil amendment is generally limited to fields in which herders are paid by local farmers to kraal their cattle (*Bos taurus*) (and thus leave the manure on the field) during the dry season, and in the areas immediately surrounding villages where local animals (goats [*Capra hircus*] and sheep [*Ovis aries*]) are kept. Millet residue is a readily available form of organic material, although it is extensively used for village industries, animal feed, and fuel during the dry season (Nicou and Charreau, 1985).

A long-term experiment was established to observe the effects of millet residue and fertilizer on millet growth. Residue was applied as a surface mulch and consisted of the aboveground stalks and leaves of mil-

Abbreviations: CEC, cation-exchange capacity; SSP, simple-super phosphate; DCB, citrate–dithionite–bicarbonate.

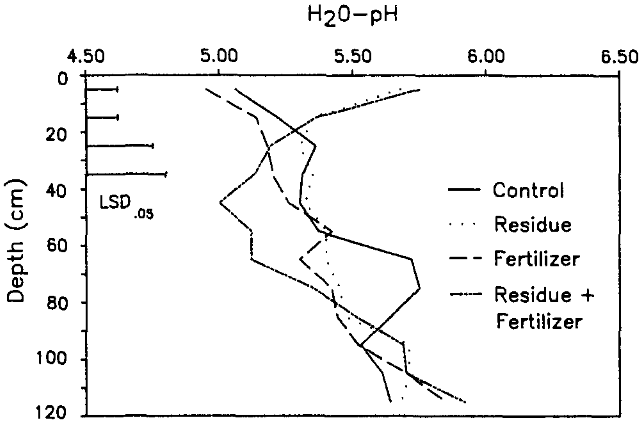

Fig. 1. Depth distribution of pH within the four residue and fertilizer treatments.

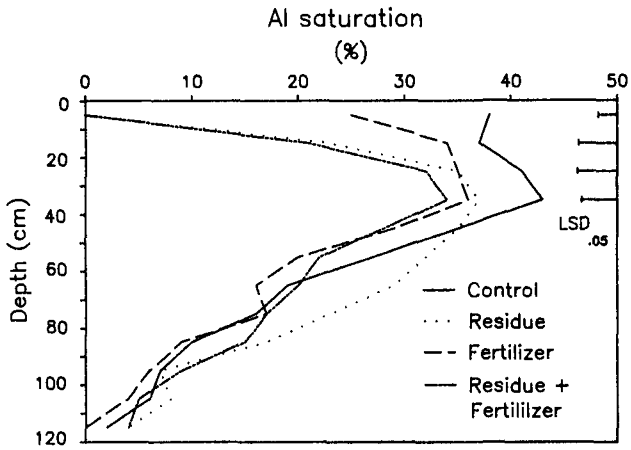

Fig. 2. Depth distribution of Al saturation within the four residue and fertilizer treatments.

let grown on the same plots in the previous year. Phosphorus (as simple-super phosphate [SSP]) and N (as urea) were applied annually at the rate of 13.0 kg P ha^{-1} and 30 kg N ha^{-1}. After 5 yr, the addition of millet residue resulted in a four-fold increase in millet biomass yield compared with the control (1662 and 346 kg ha^{-1}, respectively). Biomass yield with fertilizer (1396 kg ha^{-1}) was slightly lower than that obtained with additions of millet residue as a surface mulch. When residues were added in combination with fertilizer, biomass was increased by approximately three-fold (4027 kg ha^{-1}) compared with that found with the fertilizer or residue additions alone (Bationo, 1987).

The objectives of this study were to examine differences in soil chemical parameters resulting from 5 yr of residue addition or fertilizer in the above-mentioned experiment, and to deduce mechanisms responsible for the increase in millet yields resulting from the addition of millet residue as a surface mulch.

MATERIALS AND METHODS

Soils

The experiment was located at the ICRISAT Sahelian Center, Sadore, Niger, ≈45 km south of Niamey. Typical geomorphology of this area is a series of sand plains (terraces) sloping towards the Niger River valley. These are composed of eolian sands deposited over a deep layer (2–8 m) of cemented laterite gravel (West et al., 1984). The field plot was located on a Labucheri soil (sandy, siliceous, isohyperthermic Psammentic Paleustalf).

Soil Sampling

Soils were sampled from three of the four replicates of the field trial during the dry season of 1987–1988 prior to field preparation for planting for the 1988 growing season. Soil samples were taken in 10-cm increments to a depth of 120 cm at two locations within each plot, and pooled into one sample. Soils were then air dried and sieved (<2 mm) prior to analysis.

A topographic survey of the research site was made on a 3 by 3 m grid pattern using standard survey techniques. The lowest grid mark on the field was used as the reference soil height and was adjusted to 0 m. Values for grid points falling within each plot were averaged, and were again averaged across the four replicates of each treatment of the field trial.

Soil Analyses

Soil pH was measured in 1 *M* KCl and 1:1 soil/water. Exchangeable acidity and Al were measured after extraction in 1 *M* KCl as described by McLean (1982). Available P was extracted using the Bray-1 procedure and P in the extract was measured by the molybdate-blue method as described by Olsen and Sommers (1982). Phosphorus sorption was measured using the method of Fox and Kamprath (1970). Exchangeable bases (Ca, Mg, K, and Na) were displaced with NH_4OAc (Thomas, 1982). Concentrations of Ca and Mg were determined by atomic absorption spectrophotometry, while K and Na were determined using flame photometry. Organic C was measured by dry combustion as described by Nelson and Sommers (1982). Soil texture was determined by the hydrometer method after dispersion with sodium hexametaphosphate (Gee and Bauder, 1986). Poorly crystalline Al and Fe oxides were extracted with ammonium oxalate as described by Schwertmann (1973), and free Fe and Al oxides were extracted with DCB as described by Jackson (1958).

RESULTS

Soil Acidity Parameters

Soil pH (1:1 soil/water) was low (<5.1) in plots without residue (Fig. 1), and was significantly higher in the two treatments receiving residue application. This effect, however, only occurred in the top 0 to 10 cm of the soil profile, below which soil pH values were similar to those of the control plots.

Distribution of Al in the control plots followed a trend opposite to that of pH (i.e., Al saturation of the exchange complex increased to the 30–40-cm depth and then decreased thereafter; Fig. 2). In plots that received crop residues, there was a complete absence of exchangeable Al in the surface 10 cm. There was also a significant decrease in Al saturation, relative to the control, after the long-term addition of fertilizer.

Scott-Wendt et al. (1988) observed a high negative correlation between millet growth and Al saturation of the soil exchange complex in variable growth patterns throughout a field in this same region. Evidence

Table 1. Exchangeable Ca, Mg, and K of the four fertilizer and residue treatments† at different depths.

	Exchangeable bases														
	Ca					Mg					K				
Depth	C	R	F	RF	LSD(0.05)	C	R	F	RF	LSD(0.05)	C	R	F	RF	LSD(0.05)
cm	$cmol_c\ kg^{-1}$														
0–10	0.08	0.27	0.20	0.44	0.04	0.04	0.15	0.05	0.16	0.02	0.04	0.08	0.05	0.09	0.01
10–20	0.09	0.17	0.21	0.21	0.07	0.07	0.08	0.06	0.08	0.03	0.05	0.07	0.06	0.08	0.01
20–30	0.13	0.13	0.23	0.17	0.06	0.08	0.07	0.10	0.07	0.04	0.05	0.07	0.06	0.09	0.02
30–40	0.15	0.14	0.26	0.21	0.08	0.10	0.08	0.09	0.07	0.03	0.06	0.08	0.06	0.08	0.01
40–50	0.20	0.17	0.29	0.24	0.10	0.13	0.09	0.14	0.11	0.03	0.06	0.08	0.05	0.07	0.01
50–60	0.24	0.20	0.36	0.33	0.06	0.18	0.17	0.18	0.18	0.06	0.06	0.07	0.05	0.07	0.01
60–70	0.25	0.27	0.34	0.33	0.07	0.26	0.18	0.22	0.27	0.06	0.06	0.07	0.05	0.06	0.01
70–80	0.32	0.25	0.33	0.35	0.08	0.24	0.25	0.23	0.24	0.03	0.06	0.07	0.05	0.06	0.01
80–90	0.32	0.31	0.37	0.35	0.06	0.28	0.21	0.28	0.27	0.04	0.05	0.07	0.04	0.06	0.01
90–100	0.36	0.33	0.37	0.41	0.06	0.27	0.25	0.29	0.31	0.04	0.05	0.07	0.04	0.06	0.01
100–110	0.35	0.37	0.37	0.40	0.10	0.28	0.24	0.30	0.34	0.04	0.05	0.06	0.04	0.05	0.01
110–120	0.38	0.42	0.43	0.45	0.07	0.26	0.32	0.31	0.27	0.08	0.05	0.05	0.04	0.04	0.01

†C = control, R = residue, F = fertilizer, and RF = residue + fertilizer treatments.

exists, however, that millet growth does not seem to be directly affected by increases in labile or solution Al (Kretzschmar et al., 1991). They hypothesized that an increase in yield following residue addition was probably a result of increased P availability following complexation of Al by organic complexes. It is worth noting that differences in soil acidity occurred only within the surface 20-cm depth of the soil profile.

Exchangeable Bases

The addition of residues resulted in higher exchangeable-base contents (Fig. 3). Calcium was the dominant cation on the exchange complex, ranging from 0.08 $cmol_c\ kg^{-1}$ at the surface to 0.45 $cmol_c\ kg^{-1}$ at the 120-cm depth (Table 1). The fertilized and residue-plus-fertilizer plots generally had higher Ca contents than the control or residue-only plots, which was probably a result of Ca additions from the SSP fertilizer. The residue-only plot, however, had a higher Ca content in the surface 10 cm than either the control or fertilized plots.

Magnesium and K levels were greater in the plots receiving residues; however, this difference was only observed in the top 20 cm. There were no treatment differences with regard to Na content (data not shown).

Available Phosphorus

The Bray-1 extractant is widely used in the Sahel and throughout West Africa as an indicator of available soil P. Phosphorus values in the surface of the control plots were low (<4.0 mg P kg^{-1}) and decreased to ≈2 mg P kg^{-1} within 20 cm of the surface (Fig. 4). Bray-1 P concentrations were relatively constant below this depth. In treatments receiving millet residue, available-P levels were significantly higher in the top 10 cm. The addition of fertilizer resulted in a large increase in available P in the surface 20 cm of the soil. Available P from the residue-plus-fertilizer plots was approximately equal to the sum of the P extracted from the residue-only and fertilizer-only plots. Differences in available P occurred only within the surface 10 to 20 cm of the soil profile.

Phosphorus Dynamics

Phosphate sorption as a function of treatment and depth is presented in Fig. 5. The application of millet

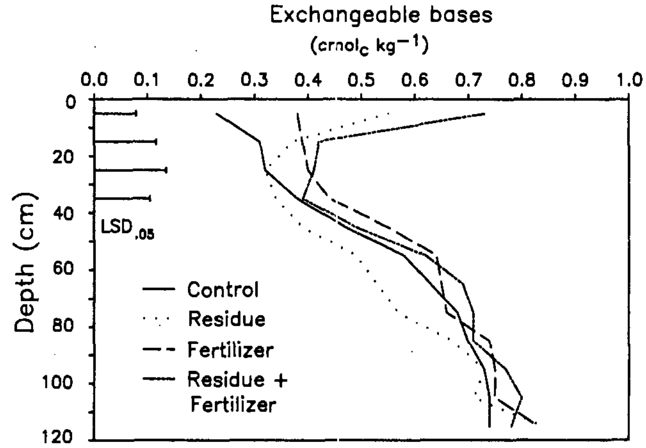

Fig. 3. Depth distribution of exchangeable bases within the four residue and fertilizer treatments.

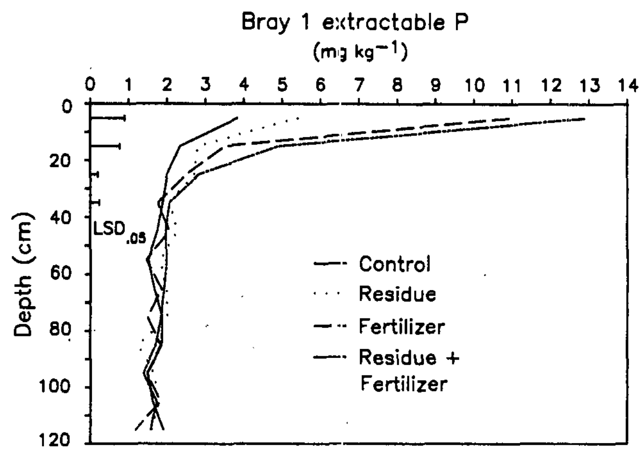

Fig. 4. Depth distribution of Bray-1 extractable P within the four residue and fertilizer treatments.

residue resulted in a decrease in P sorption in the top 0 to 10 and 10 to 20 cm. Below the 20-cm depth, however, there were no significant differences between treatments.

The P-sorption maxima were most highly correlated with clay content, exchangeable Al, and free Fe- and Al-oxide phases of these soils (Table 2). Available P

Table 2. Simple correlation coefficients (*r*) relating selected soil chemical parameters to P occurrence and availability.

Soil parameter	Total P	Bray-1 P	Sorption maxima (*b*)
	r		
Clay (%)	0.20	−0.39***	0.86†
Exchangeable Al (cmol$_c$ kg^{-1})	0.17	−0.50†	0.78†
Ammonium oxalate extractable			
Al	0.39***	−0.11	0.28
Fe	−0.24	−0.70†	0.69†
Citrate–dithionite-extractable			
Al	0.35**	−0.39***	0.73†
Fe	0.38**	−0.38**	0.67†

,*,†Significant at the 0.01, 0.001, and 0.0001 probability levels, respectively.

Table 3. Organic-C contents in the top 30 cm of soil in each treatment.

Treatment	Organic-C contents		
	0–10 cm	10–20 cm	20–30 cm
	g kg^{-1}		
Control	2.1	2.0	1.7
Residue	2.1	2.1	1.9
Fertilizer	1.9	1.9	2.0
Residue + fertilizer	2.1	2.0	2.0
LSD(0.05)	0.4	0.2	0.2

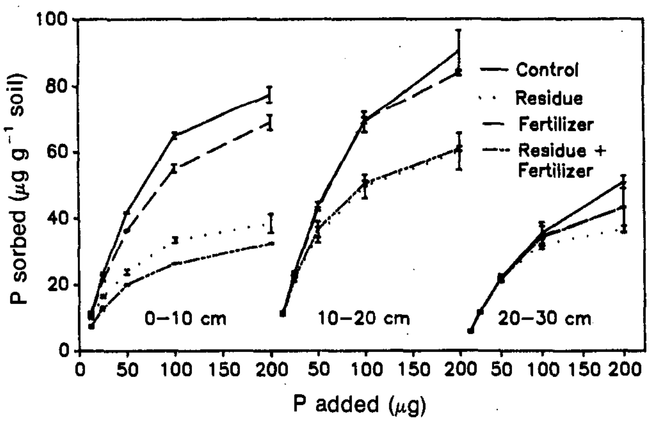

Fig. 5. Phosphorus sorption at three depths within the four residue and fertilizer treatments. Vertical bars indicate standard deviations.

was most highly correlated with the poorly crystalline phases of Fe and Al (oxalate extractable), while total P was weakly correlated with the free Fe- and Al-oxide phases. These findings are in agreement with other studies conducted within the Sahel (Manu et al., 1991).

Organic Carbon

Organic-C levels in the top 30 cm were low, ranging between 1.7 and 2.2 g kg^{-1} (Table 3). There were no significant differences in organic-C levels between treatments.

The results of these analyses indicated that the relatively low organic-matter levels found in sandy soils of the Sahel probably reflected the equilibrium level attained within this climatic zone. This relative equilibrium is highly influenced by termite activity, which is high in this environment. Field observations indicate that crop residues applied as a surface mulch can be consumed by termites within 1 yr of application.

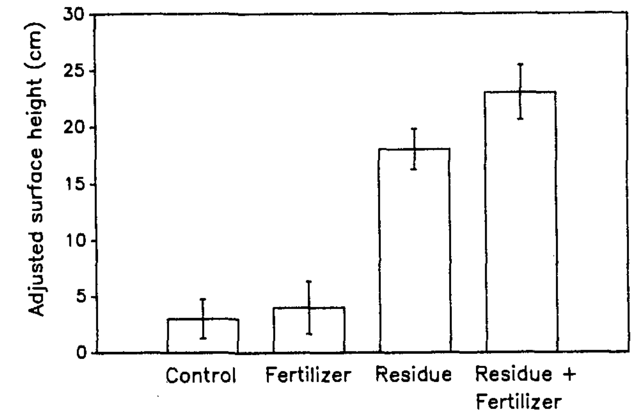

Fig. 6. Adjusted surface height of each treatment relative to the lowest elevation in the field. Vertical bars indicate standard deviations.

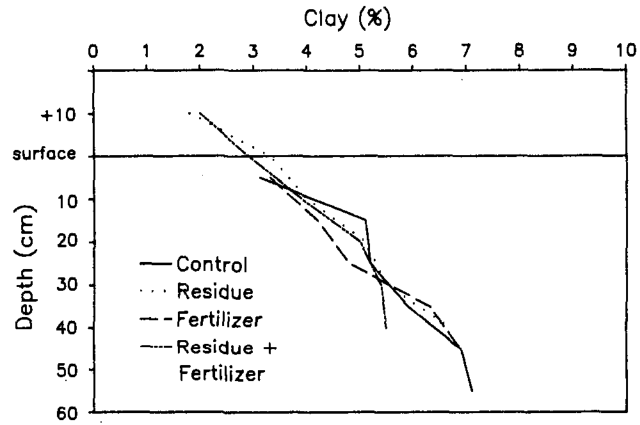

Fig. 7. Clay content throughout the soil profile after adjustment for differences in relative surface height of each treatment.

Soil Surface Topography

Observations of the experimental area showed clear micro-topographic differences between plots with and without residue addition as a surface mulch (Fig. 6). There was no significant difference in surface elevations between the control and the fertilizer plots. Addition of residue for 5 yr, however, resulted in a 15-cm increase in soil surface elevation when compared with the control plots. The use of residue plus fertilizer resulted in a slightly higher surface (≈20 cm) when compared with the control plots.

Clay contents were plotted after adjusting for the average relative difference in surface elevation between treatments (Fig. 7). Clay contents of the top 20 cm of the residue plots were lower than those of the control and fertilizer plots. This phenomenon suggests that the surface soils on the residue plots were composed of materials completely different from those of the surfaces of the control and fertilizer plots.

DISCUSSION

The increase in soil fertility following the application of millet residue as a surface mulch could be due to the recycling of nutrient elements from the residue, or the effect of the residue in entrapment of soil materials or stabilization of the surface soil.

Nutrient Recycling

Beneficial elements are recycled to the soil through termite and microbial decomposition of the millet residue (Pichot, 1975). Recent data (Bationo et al., 1990) shows that nutrient cycling may be an important aspect of the residue effect within this field trial. After the third year of operation (1985), they observed that the additions of residue resulted in a 268% increase in stover yield, compared with the control plots, with a 288% difference in uptake of N, 240% in P, 212% in Ca, 260% in Mg, and 311% in K. In a study of the N balance in this trial, it was concluded that the enhancement of millet growth by residue additions might be due, in part, to an increase in numbers of N_2-fixing bacteria, which increased root surface area and N contents, resulting in an increased uptake of P (Bley et al., 1990). As P has been determined to be the most limiting nutrient in the sandy soils of this region, any increases in available P will have a large effect on millet growth.

Eolian Component

The fact that differences in soil chemical parameters and clay contents were found only in the top 20 cm of the soil profile, and that this corresponded with the difference in elevation between the plots with and without applied residue, indicates that factors other than nutrient recycling were operative in the improvement of soil productivity.

Possible reasons for the elevated surface found in the plots receiving residue additions are: (i) a buildup of the soil surface by the entrapment of wind-blown material, or (ii) the stabilization of the original soil surface against wind erosive forces. Local farmers are aware that these mechanisms operate simultaneously in this environment (Taylor-Powell 1990).

In the Sahelian environment, finer soil particles are suspended and can be transported for long distances, while coarser materials move mainly by saltation or surface creep. Scott-Wendt et al. (1988), in a study at the ICRISAT Sahelian Center on soil microvariability and its effects on millet growth, observed that trapped eolian sands had chemical properties similar to those of the surface of nearby fertile soils, indicating a local origin. The surface of adjacent infertile soils had lower available-P and exchangeable-base contents, and were higher in exchangeable Al.

Low-productivity soils in the Sahel are often associated with wind- and water-eroded surfaces. Chase and Boudouresque (1987) found that the trapping of a surface layer of eolian material in a barren, crusted soil on a laterite plateau resulted in natural revegetation of the treated area. This revegetation was related to better fertility and improved water infiltration in areas where the material was trapped. It is commonly observed that eroded soils in which eolian material has been trapped often support a good level of millet production. These results tend to confirm the relationship between soil productivity and the protection of the soil surface.

It is also possible that suspended dusts are trapped in the residue. This material, however, could be of distant origin. Suspended dusts collected in Niger have been calculated to contribute up to 6, 1, 2, and 0.7 kg ha^{-1} yr^{-1} of Ca, Na, K, and Mg, respectively, to the soil (Drees et al., 1990). These dusts had higher clay and lower sand contents than local soils. The rough surface conditions created by the residue would enable the entrapment of a portion of the suspended material, thus contributing to nutrient cycling within this environment.

The implication of this study are that crop residues used as surface mulches in the semiarid tropics of West Africa are an important component in the improvement or regeneration of degraded or low-productivity soils through the entrapment of eolian materials, which form a fertile surface layer of soil.

ACKNOWLEDGMENT

This research was supported, in part, by TropSoils CRSP Grant no. DAN-1311-G-SS-1083-00 of the U.S. Agency for International Development (USAID).

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