Uhland, R.R. 1950. Physical properties of soil as modified by crops and management. Soil Sci. Soc. Am. Proc. 14:361–366.

Voorhees, W.B., and M.J. Lindstrom. 1984. Long-term effects of tillage method on soil tilth independent of wheel traffic compaction. Soil Sci. Soc. Am. J. 48:152–156.

Wicks, G.A. 1984. Integrated systems for control of downy brome (*Bromus tectorum*) in cropland. Weed Sci. 32(Suppl.)1:26–31.

Wicks, G.A. 1997. Survival of downy brome seed in four environments. Weed Sci. 45:225–228.

Wicks, G.A., O.C. Burnside, and C.R. Fenster. 1971. Influence of soil type and depth of planting on downy brome seeds. Weed Sci. 19:82–86.

Wicks, G.A., D.E. Smika, and G.W. Hergert. 1988. Long-term effects of no-tillage in a winter wheat (*Triticum aestivum*)–sorghum (*Sorghum bicolor*)–fallow rotation. Weed Sci. 36:384–393.

Wiese, A.F., C.D. Salisbury, and B.W. Bean. 1995. Downy brome, jointed goatgrass, and horseweed in fallow. Weed Technol. 912: 249–254.

Zuzel, J.F., J.L. Pikul, Jr., and P.E. Rasmussen. 1990. Tillage and fertilizer effects on water infiltration. Soil Sci. Soc. Am. J. 54:205–208.

Mechanisms of Residue Mulch-Induced Cereal Growth Increases in West Africa[1]

Andreas Buerkert,* André Bationo, and Komlan Dossa

ABSTRACT

The use of crop residues (CR) has been widely reported as a means of increasing crop yields across West Africa. However, little has been done to compare the magnitude and mechanisms of CR effects systematically in the different agro-ecological zones of the region. To this end, a series of field trials with millet (*Pennisetum glaucum* L.), sorghum [*Sorghum bicolor* (L.) Moench], and maize (*Zea mays* L.) was conducted over a 4-yr period in the Sahelian, Sudanian, and Guinean zones of West Africa. Soils ranged in pH from 4.1 to 5.4 along a rainfall gradient from 510 to 1300 mm. Treatments in the factorial experiments were three CR rates (0, 500, and 2000 kg ha^{-1}) and several levels of phosphorus and nitrogen. The results showed CR-induced total dry matter (TDM) increases in cereals up to 73% for the Sahel compared with a maximum of 16% in the wetter Sudanian and Guinean zones. Residue effects on weakly buffered Sahelian soils were due to improved P availability and to a protection of seedlings against wind erosion. Additional effects of CR mulching on topsoil properties in the Sahel were a decrease in peak temperatures by 4 °C and increased water availability. These mulch effects on soil chemical and physical properties strongly decreased from North to South. Likely explanations for this decrease are the decline of dust deposition and wind erosion hazards, the higher soil clay content, lower air temperature, and a faster decomposition rate of mulch material with increasing rainfall from the Sahel to the Sudanian and Guinean zones.

Low availability of mineral nutrients severely limits primary production and particularly crop growth on acid, sandy soils in sub-Saharan West Africa above 300 mm of annual rainfall (Penning de Vries and van Keulen, 1982; Bationo and Mokwunye, 1991). Given the low clay contents in West African soils and that kaolinite is the dominant clay mineral, soil cation exchange capacity (CEC) mainly depends on the organic carbon content of the topsoil. The current fertility status of these soils may be explained by a number of factors: age and origin of the soils, leaching, soil erosion by wind and water, short fallow periods, and continued nutrient mining of cropped fields (Stoorvogel and Smaling, 1994).

Under these conditions, application of mineral N and P fertilizers and even crop residues (CR) surface applied at 2000 kg ha^{-1} yr^{-1} have been reported to cause large yield increases in pearl millet across the southern Sahel (Bationo and Mokwunye, 1991; Bationo et al., 1992, 1993, 1995). For the sub-humid rainforest zones of West Africa with a bimodal annual precipitation of up to 1600 mm, many studies have documented changes in physical and chemical soil parameters as causes for mulch-induced crop growth increases (De Vleeschauwer et al., 1978, 1980; Lal et al., 1980; Maurya and Lal, 1981). However, most of this research was conducted in western Nigeria on moderately sloping Paleustalfs or Luvisols of pH $>$ 6. Furthermore, excessive rates of mulch application of up to 24 Mg ha^{-1} yr^{-1} were used. For the inner part of West Africa, the northern Guinean, the Sudanian, and the southern Sahelian zones, where annual average rainfall declines from 1300 to 300 mm and total biomass production is much lower, the causes of CR effects on crop growth and their declining magnitude from North to South are still poorly understood (Bationo et al., 1995). For the Sahel, with its many crust prone sandy soils (Hoogmoed and Stroosnijder, 1984; Valentin and Bresson, 1992), most reported data come from a very limited zone with rainfall ranging between 500 and 600 mm. For this area, mulch effects have been attributed to increased P availability (Kretzschmar et al., 1991), more vigorous root development (Hafner et al., 1993b), enhanced potassium (K) nutrition (Rebafka et al., 1994), protection of young seedlings against soil coverage during sand storms (Michels et al., 1995b), and a decrease in the penetration resistance of the soil surface that affect emergence and root growth of seedlings (Buerkert and Stern, 1995).

A. Buerkert, Institute of Crop Science, Univ. of Kassel, Steinstr. 19, D-37213 Witzenhausen, Germany; A. Bationo, International Fertilizer Development Center (IFDC) at International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Center, B. P. 12404, Niamey, Niger; K. Dossa, IFDC-Africa, B.P. 4483, Lomé, Togo. Joint contribution from Univ. of Hohenheim and ICRISAT Sahelian Ctr., ICRISAT journal article no. 2109. Research supported by the Deutsche Forschungsgemeinschaft (SFB 308). Received 9 Nov. 1998. *Corresponding author (buerkert@wiz.uni-kassel.de).

Published in Soil Sci. Soc. Am. J. 64:346–358 (2000).

[1]Dedicated to Horst Marschner and his commitment to process-oriented soil fertility research in West Africa.

Abbreviations: CAN, calcium ammonium nitrate; CEC, effective cation exchange capacity; CR, crop residues as cereal stover; DAS, days after sowing; NPK, 15-15-15 mineral fertilizer with 15% N, 15% P_2O_5, and 15% K_2O; SSP, single superphosphate; TDM, total dry matter; TRP, Tahoua rock phosphate.

Given the urgent need to stabilize agricultural production in the region, a better understanding and subsequent prediction of CR effects on a regional scale is important. The purpose of this research was therefore (i) to verify the mechanisms of CR response at a number of sites in the Sahel and (ii) to measure with an identical experimental setup CR effects under the higher rainfall conditions of the Sudanian and northern Guinean zones.

MATERIALS AND METHODS

The data presented in this paper are based on three rainfed experiments. Two experiments were conducted from 1991 to 1994 at ICRISAT Sahelian Center, Sadoré, Niger (13°14′N latitude, 2°17′E longitude, 235 m altitude) on a siliceous, isohyperthermic Psammentic Paleustalf (West et al., 1984). Total annual rainfall was 592 mm in 1991, 511 mm in 1992, 533 mm in 1993, and 794 mm in 1994 compared with a long-term average of 560 mm. The experiments at ICRISAT were designed to clarify cause-effect relationships involved in CR-induced increases of cereal growth in the Sahel.

The purpose of the third experiment was to compare CR effects from the Sahel with those from higher rainfall areas. This experiment consisted of a series of multi-factorial trials conducted from 1995 to 1998 at eight sites selected to provide a gradient of annual rainfall from 510 to 1300 mm and corresponding increases in clay contents from 2 to 16%. The soil types at the chosen sites were in the Sahel Psammentic Paleustalfs at Banizoumbou (13°31′N, 2°39′E; Niger), Sadoré (13°14′N, 2°17′E; Niger), Kara Bedji (13°15′N, 2°32′E; Niger), and Goberi (12°58′N, 2°50′E; Niger); in the Sudanian zone an Arenic Kandiustalf at Gaya-Bengou (11°59′N, 3°32′E; Niger) and a Haplustalf at Fada-Kouaré (11°59′N, 0°19′E; Burkina Faso); and in the Northern Guinean zone an isohyperthermic Plinthic Kanhaplustult at Koukombo (10°17′N, 0°23′E; Togo) and an Isohyperthermic Plinthustalf at Kaboli (8°45′N, 1°35′E; Togo). The sites reflected the typical range of total rainfall in the region with a single unimodal duration of 4 to 6 mo. Topsoil values for organic carbon (C org), P-water, CEC, and base saturation were also typical for the region (Table 1). All eight sites, except Kara Bedji, which had a slope of about 2%, were completely flat and did not show any sign of water erosion over the 4 yr of the experiment.

Experiment 1

To study CR effects on the chemical and physical properties of the topsoil, data were collected from a soil fertility trial conducted from 1991 to 1993. The site was cleared after 8-yr growth of a typical bush fallow with the shrub *Guiera senegalensis* J.F. Gmel. then cultivated with millet at a rate of 10 000 planting holes (pockets) ha^{-1} in the first rains in May 1991. The 48 factorial treatments assigned to 10- by 10-m plots in a completely randomized design with two replications consisted of (i) four millet genotypes, (ii) three levels of millet stalks (CR), (iii) P fertilizer broadcast at a rate of 0 and 13 kg P ha^{-1} as single superphosphate (SSP) shortly before sowing, and (iv) N fertilizer applied as calcium ammonium nitrate (CAN) at 0 and 30 kg N ha^{-1}. Crop residues harvested from the corresponding plots were broadcast in early May 1991 and again in November 1992 and 1993 on the soil surface as stalks at rates of 500 and 2000 kg dry matter ha^{-1}. A third mode of application was the spreading of ash from 2000 kg burned CR ha^{-1} prior to planting that was surface-incorporated with a rag (“unmulched”). Ash plots received a supplement of elemental sulfur and N as CAN to account for volatilization losses at CR burning.

Plots with 500 and 2000 kg ha^{-1} of CR mulch were split in two parts at the end of 1993, to study the short-term effects of CR application on soil properties and millet growth. One part received an additional (fourth) CR application after millet harvest in November 1993, whereas on the other part residues were withheld until April 1994. Average total mineral nutrient concentrations in the mulched millet stalks were 0.81% N, 0.05% P, and 2.2% K. Details on yearly rainfall, management operations, plant harvest, and pest protection have been reported previously (Buerkert and Stern, 1995).

Plant Sampling

At final harvest, four central rows of millet were cut, shoots and heads separated and dried to constant weight at 65°C, and shoot total dry matter (TDM) was determined. For determination of mineral nutrient concentrations, all plant material was ground to pass through a 2-mm sieve. Total N was determined with a Macro-N-Analyzer (Heraeus, Bremen, Germany). For P and K determination, samples were ashed for 4 h at 500°C in a muffle furnace and the ash dissolved in 1:30 (v/v) diluted HCl. Potassium was analyzed by flame-emission photometry (Eppendorf, Elex 6361, Ismaning, Germany) and total P colorimetrically (Hitachi U-3300 spectrophotometer) according to the vanado-molybdate method (Gericke and Kurmies, 1952). To determine treatment effects on input-output balances of N, P, and K, the amount of these nutrients taken up in the stover and grain (plant nutrient output) was deducted from the amount of nutrients applied with the respective levels of mulched stalks and mineral P fertilizers (nutrient input).

Soil Sampling

To measure treatment effects on chemical properties of the topsoil, initial samples were taken before the onset of the experiment in May 1991 from 0 to 0.2 m at four locations in

Table 1. Mean annual precipitation and initial soil chemical parameters at 0- to 0.2-m depth for eight sites in West Africa in May 1995.

Site	Precipitation†	Clay	pH‡	P-water	P-Bray	CEC$_e$§	BS¶	C org	N min
	mm	%		µg kg^{-1}	mg kg^{-1}	cmol$_c$ kg^{-1}	%	g kg^{-1}	mg kg^{-1}
Banizoumbou	510	5	4.4	300	1.5	0.8	74	1.50	5
Sadoré	560	3	4.5	440	2.8	1.1	86	2.26	n.a.
Kara Bedji	590	4	4.2	130	1.9	0.8	56	1.57	4
Goberi	600	3	4.1	280	1.7	0.8	50	1.55	2
Gaya	800	13	4.2	140	2.5	1.3	66	3.30	9
Fada	850	15	5.4	320	1.3	2.8	99	5.20	3
Koukombo	1100	5	5.6	1100	2.0	1.9	97	3.67	12
Kaboli	1300	16	4.7	1250	3.8	3.3	71	6.47	18

† Average annual rainfall of 5 to 10 yr.
‡ pH in 0.01 *M* KCl (1:2.5).
§ Effective cation-exchange capacity.
¶ Base saturation.
n.a. = not available.

Table 2. Treatment combinations in a multi-factorial experiment with crop residue mulch and mineral fertilizer application from 1995 to 1997 in West Africa.

N†	CR	Control w/o P	SSP_{13}	TRP_{39}	$P_{4\ placed}$	TRP_{39} $+P_{4\ placed}$	RP_{130}	TRP_{130} $+P_{4\ placed}$	RP_{130} $+P_{4\ placed}$
0	500	X	X	X	X	X	X	X	X
0	2000	X	X	X		X			
30	500	X	X	X		X			
30	2000	X	X	X		X			
60	500	X	X	X	X	X	X	X	X
60	2000	X	X	X		X			
90	500	X	X	X		X			
90	2000	X	X	X		X			

† CR = Crop residue (CR) mulch applied at farmers' traditional rate (500 kg ha^{-1}; control) and 2000 kg ha^{-1}.
N = applied as calcium ammonium nitrate (CAN) at 0, 30, 60, and 90 kg N ha^{-1}.
SSP = Single superphosphate at 13 kg P ha^{-1}.
TRP = 'Soft' rockphosphate from Tahoua (Niger) at 39 and 130 kg P ha^{-1}.
RP = 'Hard' rockphosphate from Kodjari (Burkina Faso) or Hahotoe (Togo) at 130 kg P ha^{-1}.
P_{placed} = hill-placed application at sowing of 4 kg P ha^{-1} as SSP (1995 and 1996) or NPK (1997 and 1998).

each plot, bulked, air-dried, and sieved to 2 mm. In May 1994, plots were sampled again at 0 to 0.1 and 0.1 to 0.2 m. Data from the initial soil sampling were used as covariates in the analysis of variance of the results from the second sampling to reduce effects of initial short-distance spatial variability on treatment effects. Separate samples were taken in both parts of the plots split in November 1993 to determine short-term mulch effects on chemical properties of the topsoil. In May 1994 additional samples were taken from 0.2- to 0.4-, 0.4- to 0.6-m, and 0.6- to 1.0-m depth in 12 plots to measure CR effects on soil chemical properties at greater depth. These plots came from both replications of all three CR levels with and without broadcast P and were all planted to the millet landrace Sadoré Local.

All samples were analyzed for pH (1:2.5 0.01 *M* KCl), C org (Walkley and Black, 1934), Bray-P1 (P-Bray; Olsen and Sommers, 1982), and exchangeable Al and total acidity (McLean, 1982). Exchangeable bases were extracted with 1 *M* NH_4-acetate and Ca and Mg were determined by atomic absorption spectrophotometry, whereas K and Na were determined by flame emission spectrophotometry. Water soluble P was determined according to Sissingh (1971) but with incubation time reduced to 5 min at a soil:water ratio of 1:10 in order to obtain only the most easily available P fractions.

To examine CR effects on soil surface crusts, bulked samples were taken in May 1994 from 16 plots with a stainless steel spoon at 0- to 10-, 10- to 20-, and 20- to 50-mm depth in plots with 2000 kg CR ha^{-1} applied as mulch or ash, with and without broadcast P. The samples were analyzed for soil chemical parameters and soil particle size distribution using the pipette method (Gee and Bauder, 1986).

To examine treatment effects on surface crusting, penetrometer measurements were collected before the onset of the rains in late April 1994. At 20 randomly chosen locations in each plot or split-plot, measurements were taken independently at 0 to 0.02 and 0 to 0.05 m. A hand-held penetrometer (Eijkelkamp, the Netherlands) was used with tips of 35-mm diam. for the upper depth and 15-mm diam. for the lower depth.

Experiment 2

Measurements were taken in a mulching experiment with millet planted at 10 000 pockets ha^{-1} from 1992 to 1994 (Buerkert et al., 1996b) to study CR effects on soil surface temperature and soil water content during the growing season. In one

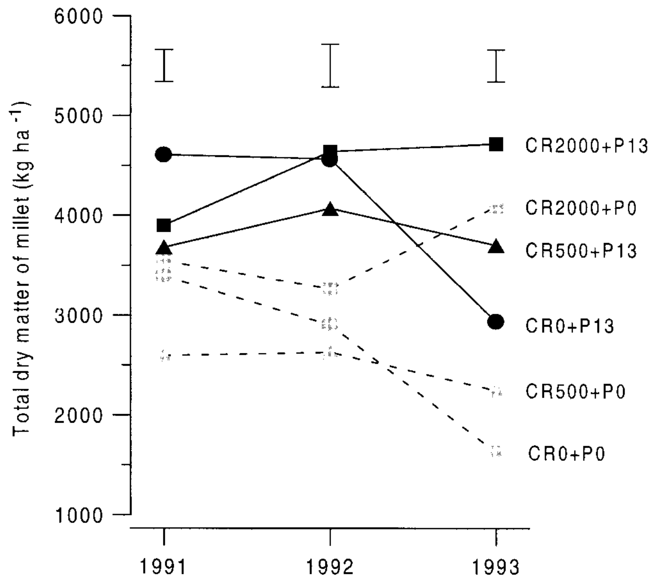

Fig. 1. Millet total dry matter production at Sadoré, Niger, as affected by phosphorus (P) applied at 0 and 13 kg P ha^{-1} as SSP and surface broadcast millet crop residues (CR) at annual rates of 500 and 2000 kg dry matter ha^{-1} or as ash (unmulched) at the rate of 2000 kg burned CR ha^{-1}. Total annual rainfall was 592 mm in 1991, 511 mm in 1992, and 533 mm in 1993. Data are means of four millet genotypes; vertical bars represent one standard error of the difference.

of the three replicates of the trial, soil surface temperature was recorded with three temperature probes (type 108, Campbell Scientific, Logan, UT) randomly placed at the 0.01-m depth in a unmulched (control) plot and in a plot mulched with 2000 kg surface applied CR ha^{-1}. Given lower variation in temperature with increasing depth, only a single copper-constantan thermocouple wire was used to measure soil temperatures at 0.05 m in each of the two plots. The differential measurements of all sensors were recorded at intervals of 20 s, averaged every 30 min and stored with a CR10 datalogger (Campbell Scientific). In all three replicates, soil water content was monitored regularly during 1993 and 1994 with a neutron probe (Troxler Int. Ltd, Research Triangle Park, NC) in three access tubes per plot at 0.1, 0.2, 0.3, 0.5, 0.7, 1.0, 1.3, and 1.6 m. The probe had been previously calibrated for this site at different depth intervals and the respective regression equations were used to calculate water contents from measured counts.

Experiment 3

The 40 mainplot treatments attributed to plots of 10 by 10 m and replicated twice at each site were factorial combinations of three factors: CR, N, and P (Table 2). Crop residues were broadcast at 500 or 2000 kg CR ha^{-1} in January of each year, the middle of the dry season. For the sites in the Sahelian and Sudanian zone, CAN was broadcast at 0, 30, 60, and 90 kg N ha^{-1} and for the sites in the Guinean zone at 0, 60, 90, and 120 kg N ha^{-1}. All N rates were split into three equal applications which were made after emergence (10 d after sowing, DAS), at thinning (25 DAS), and at booting (50 DAS). The eight P levels were (i) a control without P, (ii) annual P placement with the seed at a rate of 4 kg P ha^{-1} (P_4) as single superphosphate (SSP) in 1995 and 1996 and as NPK in 1997, (iii) annual broadcast P at 13 kg P ha^{-1} as SSP (SSP_{13}), broadcast P as 'soft' Tahoua rock phosphate (TRP) at a 3-yr rate of 39 kg P ha^{-1} (iv) with and (v) without seed placement of

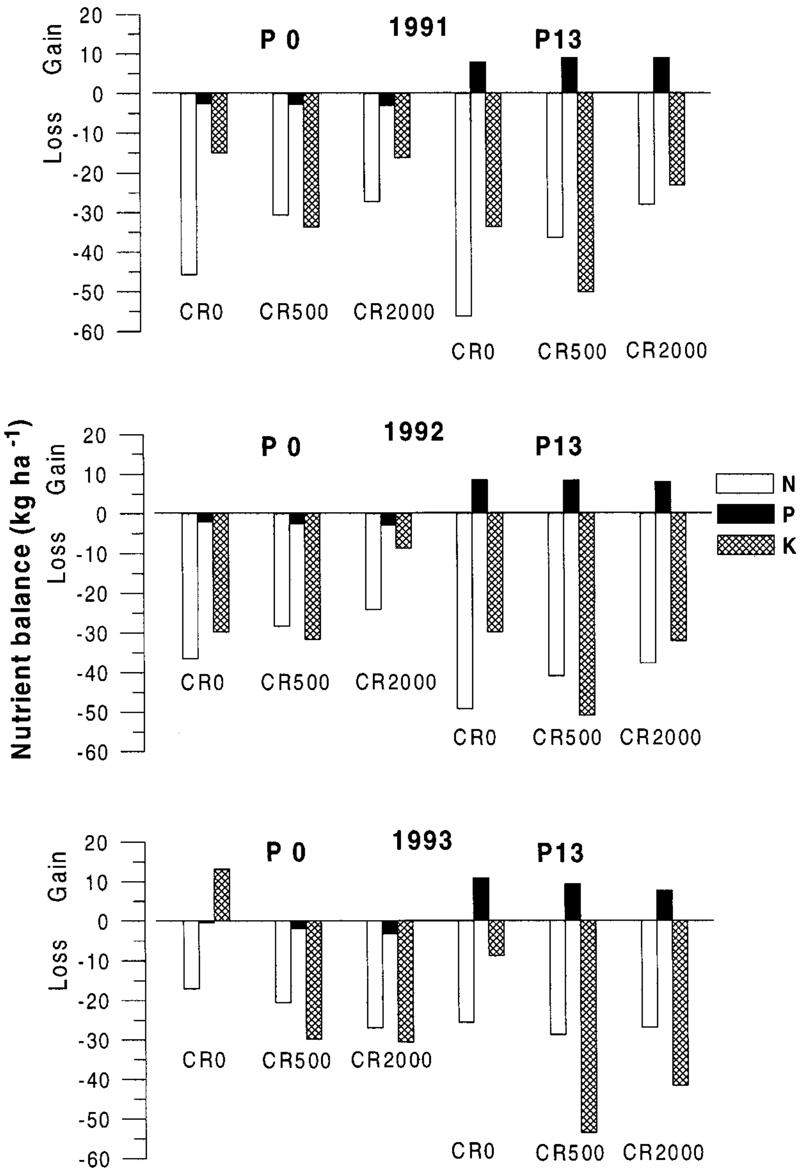

Fig. 2. Nutrient balances for nitrogen (N), phosphorus (P), and potassium (K) as affected by P applied at 0 and 13 kg ha^{-1} as SSP and surface broadcast millet crop residues (CR) at annual rates of 500 and 2000 kg dry matter ha^{-1} or as ash (unmulched) at the rate of 2000 kg burned CR ha^{-1}. Data are means of 16 replicates. Sadoré, Niger, 1991 to 1993.

SSP (TRP_{39} and $TRP_{39}+P_4$), (vi) as "soft" rock phosphate at a 10-yr rate of 130 kg P ha^{-1} (TRP_{130}) or as "hard" rock phosphate at a 10-yr rate of 130 kg P ha^{-1} (vii) with and (viii) without seed placement of SSP (RP_{130} and $RP_{130}+P_4$). At the Burkina site, the hard rock phosphate was from Kodjari and in Togo from Hahotoe. Despite generally higher TDM production in the wetter zones and differences in the cereal species sown, CR mulch and P levels were kept constant to facilitate the comparison of treatment effects on crop growth and soil properties across environments. In Niger (Kara Bedji, Banizoumbou, Sadoré, Goberi and Gaya), the crop sown was millet at 10 000 pockets ha^{-1}. In Burkina Faso (Kouaré) sorghum was sown at 40 000 pockets ha^{-1}, and in Togo (Koukombo and Kaboli) maize at 53 330 pockets ha^{-1}.

Plant and Soil Sampling

At harvest, the pockets of each plot, with the exception of border rows, were cut as stated earlier and the dry weight of grain, heads, and remaining straw determined to compute TDM. At two sites in each of the three climatic zones (Kara Bedji, Goberi, Gaya, Fada, Koukombo, and Kaboli), the topsoil was sampled before the onset of the third rainy season. Five subsamples were taken in both replicates of eight selected treatments at depths of 0 to 0.1 and 0.1 to 0.2 m. Plots sampled comprised the two CR levels (500 and 2000 kg ha^{-1}) without N application at three levels of P (control, SSP_{13}, and TRP_{39}) and two additional P levels (SSP_4 and TRP_{130}) at 500 kg CR ha^{-1}. Subsamples were bulked, dried, sieved, and analyzed for soil chemical parameters as stated above.

Statistical Analysis

GENSTAT (Lawes Agricultural Trust, 1993) was used to compute *F*-statistics with analyses of variance and standard errors of the difference. Wherever applicable, depth intervals were treated as split-plots thereby taking into account their spatial dependence. Some of the plant dry matter data were

Table 3. Effects of broadcast phosphorus (P) fertilizer and crop residue (CR) application on chemical properties of the surface soil crust at 0- to 50-mm depth after 3 yr of treatment.

Soil property	Dept (mm)	P 0 CR0†	P 0 CR2000	P 13 CR0	P 13 CR2000	sed‡	*F*-Probability	
pH KCl	0–10	4.51	5.28	4.94	5.30	0.14	CR	<0.001
	10–20	4.47	5.28	4.60	5.12		P	0.840
	20–50	4.39	5.05	4.39	4.53		P × CR	0.060
P-water (μg kg^{-1})	0–10	527	751	547	819	78	CR	<0.001
	10–20	456	755	518	855		P	0.107
	20–50	433	685	522	675		P × CR	0.946
P-Bray (mg kg^{-1})	0–10	4.9	5.3	7.2	9.3	0.7	CR	<0.001
	10–20	3.7	5.7	6.8	13.2		P	<0.001
	20–50	3.2	5.2	5.4	10.3		P × CR	0.004
K (mmol kg^{-1})	0–10	0.88	1.07	1.03	1.15	0.21	CR	0.124
	10–20	0.97	1.32	1.13	1.35		P	0.557
	20–50	0.80	1.25	1.03	1.15		P × CR	0.557
Base saturation (%)	0–10	87.6	96.0	94.1	96.8	4.4	CR	0.013
	10–20	85.6	97.6	88.6	96.3		P	0.929
	20–50	81.3	96.5	81.4	89.1		P × CR	0.342
C org (g kg^{-1})	0–10	2.04	1.14	1.75	1.55	0.31	CR	0.870
	10–20	1.86	1.71	2.09	2.38		P	0.320
	20–50	1.71	2.23	1.78	2.43		P × CR	0.324

† With ash application from burned 2000 kg CR ha^{-1}.
‡ Standard error of the difference.

examined for normal distribution of residuals with SAS version 6.06 (SAS Institute, 1991). Occasionally minor deviations were found but data transformations had very little influence on the *F*-values. For consistency, it seemed appropriate to present statistics of untransformed data while being aware that true probabilities may slightly differ from those shown.

RESULTS

Experiment 1

Plant Growth

Depending on the P level, mulch-induced effects on millet TDM were negligible or even slightly negative in the first 2 yr after the prolonged period of fallow at this site but increased in 1993 across P levels leading to almost twice the TDM compared with unmulched (ash) plots (Fig. 1). Plots with ash application had their highest yields in the first year after the prolonged fallow and were still more productive than plots with 500 kg ha^{-1} of CR mulch in 1992. In 1993, however, TDM yields in ashed plots collapsed regardless of the P level applied. The dynamics of residue-induced increases in millet growth after repeated cultivation became obvious with the split-plot application in 1994. Across P levels, the early fourth mulch application led to millet TDM increases of 430 kg ha^{-1} and 1010 kg ha^{-1} with the low and high CR mulch rate, respectively, as compared with the delayed mulch application in April (Muehlig-Versen, 1994, unpublished data). In contrast to the time-dependent cumulative effects of mulching on crop

Table 4. Effects of 3 yr of surface mulched crop residue (CR) application at 0 (unmulched with ash application), 500 and 2000 kg CR ha^{-1} with and without phosphorus (P) as broadcast single superphosphate at 13 kg P ha^{-1} on soil pH (in 0.01 *M* KCl), water soluble phosphorus (P-water), P-Bray, exchangeable potassium (K), base saturation, and organic carbon (C org) at two depths. Sadoré, Niger, 1991–1994.

Soil property	Depth (m)	P 0 CR0	P 0 CR500	P 0 CR2000	P 13 CR0	P 13 CR500	P 13 CR2000	sed†	*F*-Probability	
pH KCl	0–0.1	4.21	4.39	4.61	4.30	4.36	4.71	0.07	CR	<0.001
	0.1–0.2	4.13	4.22	4.37	4.19	3.23	4.42		P	0.284
									P × CR	0.444
P-water (μg kg^{-1})	0–0.1	404	464	571	447	509	588	45.5	CR	<0.001
	0.1–0.2	341	335	422	321	414	467		P	0.167
									P × CR	0.656
P-Bray (mg kg^{-1})	0–0.1	3.7	4.3	4.5	6.5	8.2	9.9	0.66	CR	<0.001
	0.1–0.2	2.8	3.7	3.3	4.7	5.7	6.7		P	<0.001
									P × CR	0.027
K (mmol kg^{-1})	0–0.1	0.89	0.92	1.22	1.01	0.83	1.35	0.08	CR	<0.001
	0.1–0.2	0.83	0.87	1.00	0.97	0.84	1.06		P	0.182
									P × CR	0.128
Base saturation (%)	0–0.1	70	76	89	78	79	92	3.5	CR	<0.001
	0.1–0.2	58	62	76	63	66	79		P	0.020
									P × CR	0.471
C org (g kg^{-1})	0–0.1	1.78	2.07	2.31	1.81	1.98	2.32	0.11	CR	<0.001
	0.1–0.2	1.54	1.57	1.61	1.72	1.63	1.75		P	0.364
									P × CR	0.589

† Standard error of the difference.

growth, the impact of SSP application at 13 kg P ha^{-1} was much more immediate, leading to TDM increases of 28% in the first, 51% in the second, and 43% in the third year of application compared with unfertilized plots (Fig. 1).

Nutrient Balances

In each year, nutrient removal strongly exceeded inputs for all mineral elements analyzed except P after SSP application and K in unmulched plots without SSP in 1993 (Fig. 2). Losses were largest for N and K, particularly after P application. Mulch application at 2000 kg CR ha^{-1} decreased net N and K losses in 1991 and 1992. However, in 1993 the reverse was true when N and K balances were most negative at the high rate of mulch (Fig. 2).

Near-Surface Soil Properties

Overall, the three uppermost surface soil layers at 0 to 10, 10 to 20, and 20 to 50 mm had higher pH, available P, exchangeable K, and base saturation than the topsoil at the 0- to 100-mm depth (Table 3 and 4). Four successive applications of CR mulch had significantly affected most of the measured chemical properties. Compared with ash application, mulching at 2000 kg CR ha^{-1} increased pH by about 0.7 units throughout the three surface layers regardless of the level of applied P. The mulch-induced increases in P-water ($P < 0.001$) averaged 51% or 256 μg P kg^{-1} across P levels and depth (Table 3). Increases in exchangeable K were large in absolute terms but statistically not significant.

Mulching also indirectly affected the particle size distribution in the surface soil leading to significantly higher proportions of clay particles (< 2 μm) and coarse sand (< 1000 μm) in mulched plots than in unmulched plots. The proportion of medium size particles (< 250 μm) tended to decrease with CR application (Table 5).

Topsoil Properties

After three consecutive CR treatment applications, both mulch rates had significantly ($P < 0.001$) affected all measured chemical properties of the topsoil at both P levels (Table 4). For P (water and Bray) and K the mulch-induced increases were particularly large in the 0- to 0.1-m layer but remained noticeable even at the 0.1- to 0.2-m depth. Phosphorus application only increased P-Bray and base saturation but did not affect P-water (Table 4). Organic carbon concentrations as a function of depth and P level were significantly higher with mulching than in unmulched plots. However, with 2.0 g C kg^{-1} in plots with 2000 kg CR ha^{-1} average C org levels after 4 yr of cultivation were across both P levels 11% lower than the initial C org concentration measured after 8 yr of bush fallow (Table 1 and 4).

The early fourth CR application in November 1993 led to significant increases of all measured soil chemical properties at the 0- to 0.1-m depth, except for P-Bray and C org, compared with the application in April 1994 (data not shown). The early CR application increased P-water by 9%, exchangeable K by 13%, and base saturation by 3% in the upper topsoil layer averaged across the two rates as compared with the late application.

Visual observations showed a strong increase in termite activity with the rate of applied mulch as evidenced by "termite roads" across plots and partial coverage of mulched stalks with soil hulls. Three consecutive CR mulch applications significantly increased surface soil penetrability at both measured depths ($P < 0.001$). At 0- to 0.02-m mechanical resistance was 320 kN m^{-2} in unmulched plots, 210 kN m^{-2} with the low mulch rate, and 200 kN m^{-2} for plots with 2000 kg CR ha^{-1}, whereas at 0 to 0.05 m, resistance values were 2950, 2570, and 2110 kN m^{-2}, respectively. A fourth mulch application right after millet harvest further decreased soil resistance ($P < 0.001$) at 0 to 0.02 m to 190 kN m^{-2} with

Table 5. Effects of crop residue application as ash (CR0) or mulch at 2000 kg ha^{-1} (CR2000) on the texture of the soil surface crust at 0– to 50-mm depth after 3 yr of treatment. Sadoré, Niger 1991 to 1994.

Texture	Depth	CR0	CR2000	sed†	*F*-Probability	
μm	mm					
<2	0–10	2.0	2.9	0.3	CR	0.002
	10–20	2.3	3.1		Depth	0.012
	20–50	2.5	3.5		CR × Depth	0.870
<16	0–10	0.3	0.6	0.2	CR	0.726
	10–20	0.5	0.6		Depth	0.199
	20–50	0.8	0.5		CR × Depth	0.010
<50	0–10	1.2	1.6	0.2	CR	0.861
	10–20	1.4	1.3		Depth	0.011
	20–50	1.9	1.4		CR × Depth	<0.001
<125	0–10	20.3	20.7	1.2	CR	0.637
	10–20	22.0	22.2		Depth	<0.001
	20–50	23.0	23.8		CR × Depth	0.867
<250	0–10	40.1	34.0	0.9	CR	0.002
	10–20	40.4	38.0		Depth	0.001
	20–50	39.0	40.0		CR × Depth	<0.001
<500	0–10	33.3	31.8	1.3	CR	0.398
	10–20	29.6	29.8		Depth	<0.001
	20–50	28.2	26.6		CR × Depth	0.326
<1000	0–10	3.0	8.4	0.8	CR	0.010
	10–20	3.9	5.2		Depth	0.008
	20–50	4.7	4.3		CR × Depth	<0.001

† Standard error of the difference.

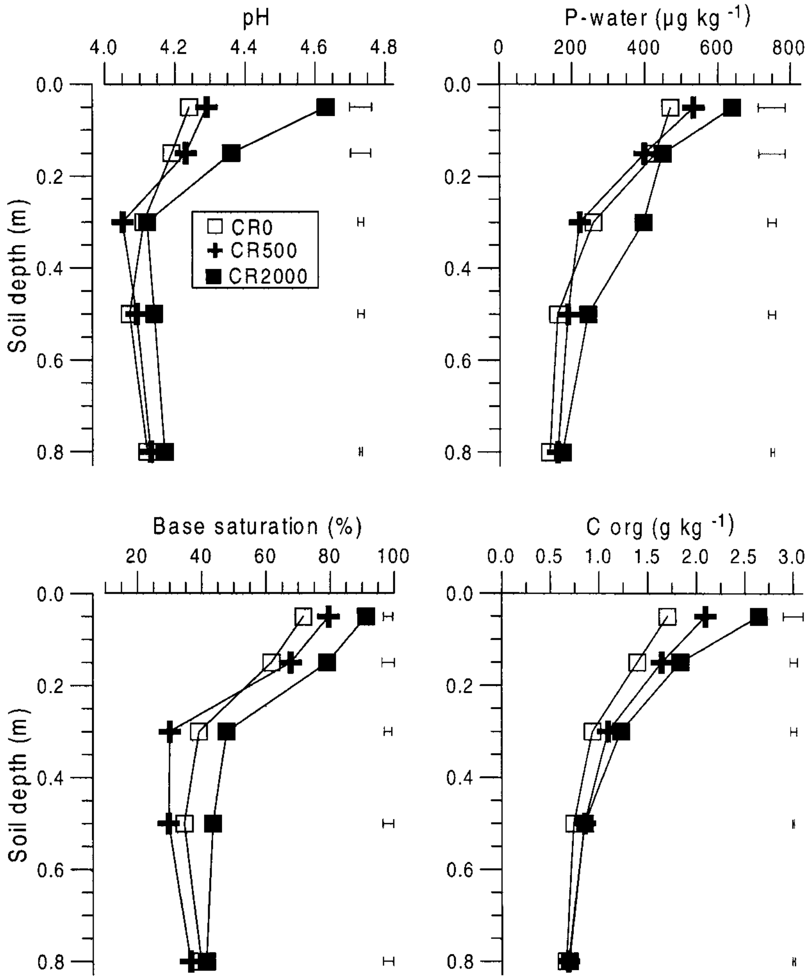

Fig. 3. Soil pH KCl, water soluble phosphorus (P-water), base saturation, and soil organic carbon (C org) concentrations in a typical profile of a Psammentic Paleustalf after 3 yr of continuous millet cultivation with annual applications of three levels of millet crop residues (CR) broadcast at 500 (CR_{500}) and 2000 (CR_{2000}) kg dry matter ha^{-1} or as ash (unmulched) at the rate of 2000 kg burned CR ha^{-1}. Data points are averages of four plots sown with the millet cultivar Sadoré Local without and with yearly application of SSP at 13 kg P ha^{-1} at Sadoré, Niger, from 1991 to 1993. Horizontal bars represent one standard error of the difference.

500 kg CR ha^{-1} and to 90 kN m^{-2} with 2000 kg CR ha^{-1}; at 0- to 0.05-m depth, the respective resistance values were 2260 and 1500 kN m^{-2}.

Chemical Properites of the Subsoil

After 3 yr of CR application, the analysis showed mulching effects to 0.3 m across P levels. The relative increases in P-water, C org, and base saturation in plots with the high mulch rate compared with unmulched plots with ash application were particularly large (Fig. 3).

Experiment 2

Surface Temperature

On clear days, mulching decreased soil surface temperatures from 0900 to 1800 h. In the early rainy season, at 1430 h temperatures at the 0.01-m depth in unmulched plots reached 44°C, whereas temperatures in mulched plots at 0.01 and 0.05 m were 4°C lower. While seedlings appeared dark green and vigorous in mulched plots, many of the seedlings in unmulched plots looked severely N-deficient, developed brown leaf tips, and subsequently died.

Soil Moisture

Treatments did not affect soil moisture contents early in the season. However in 1993, with heavy rains in August, water contents in mulched plots by early September were higher than in unmulched control plots to a depth of 0.7 m (Fig. 4 a). Differences were even more marked ($P < 0.10$) in the wetter year of 1994 when mulching strongly increased soil water contents throughout the profile in August and to 0.3 m in September (Fig. 4 b and c).

Experiment 3

Plant Growth

Despite large variations in average TDM levels across sites and years (Table 6) a distinct difference in CR

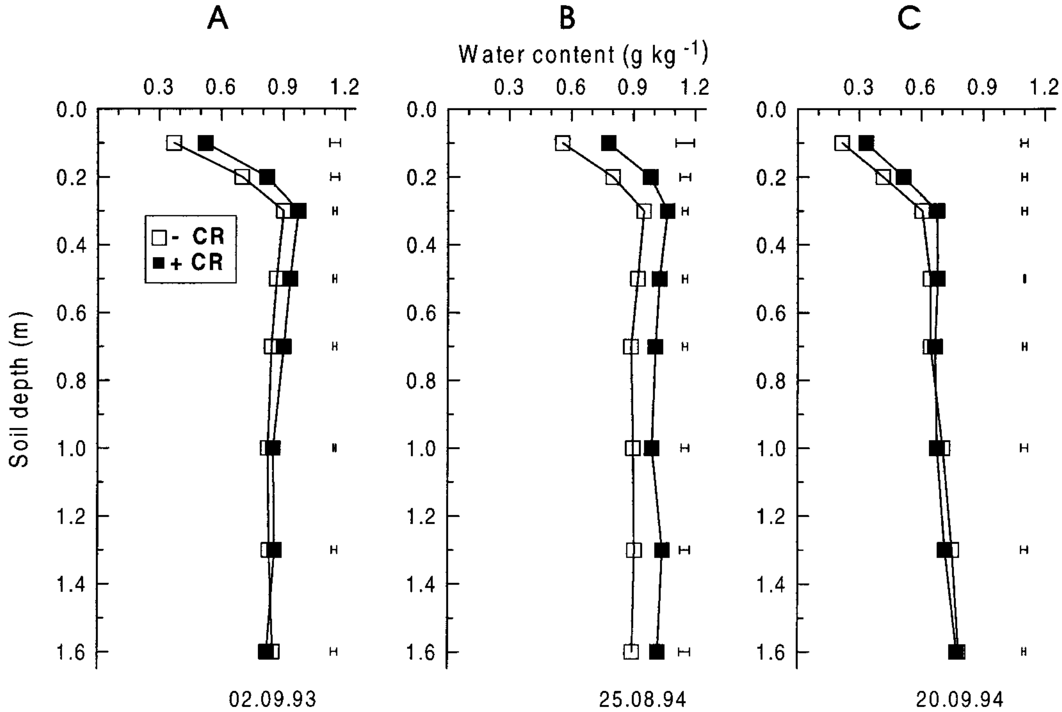

Fig. 4. Soil water contents from 0.1 to 1.6 m with and without surface mulched crop residues (+/− CR) at 2000 kg ha^{-1}. Data were measured at Sadoré, Niger, in early September 1993 (A), late August 1994 (B), and mid September 1994 (C) and are means of three subsamples in each of the three replicates. Horizontal bars represent one standard error of the difference.

effects on cereal growth was observed between the Sahelian sites and the Sudano-Guinean sites. In the Sahel after the first year, CR mulch at 2000 kg ha^{-1} resulted in cereal TDM increases of up to 72% compared with 500 kg ha^{-1}. In contrast, at the four sites in the Sudanian and Guinean zone TDM differences between the two mulch rates varied between −10% and +15% (Fig. 5).

Topsoil Properties

Residue effects on soil chemical properties closely mirrored those on plant growth and declined with increasing rainfall from North to South. For Kara Bedji in the Sahel, changes in soil properties were very similar to those at Sadoré obtained in experiment 1 (Table 7). Compared with 500 kg CR ha^{-1}, the application of 2000 kg CR ha^{-1} for 2 yr resulted in increases in pH, available P, and extractable K. The high mulch rate also raised the base saturation and helped maintain the initial level of C org (Table 1). For Goberi, the Sahelian site with the highest rainfall and the largest clay content, CR effects on chemical soil properties were detectable but much smaller than at Kara Bedji (Table 7). Compared with the Sahel, mulching effects on pH or base saturation were minor in the Sudanian and Guinean zone. Nevertheless, the high mulch rate caused a significant increase in C org at Gaya as compared with the low rate of 500 kg CR ha^{-1} (Table 8). Residue effects on P-Bray were inconclusive but the concentration of P-water, a particularly sensitive indicator for CR effects in the Sahel, was consistently lower throughout the Sudanian and Guinean zone at the high CR mulch rate as compared with the low rate. At 0 to 0.2 m, the percentage decrease in P-water with the high compared with the low mulch rate was 33% at Gaya, 22% at Fada, 9% at Koukombo, and 27% at Kaboli (Table 8). After 2 yr of cultivation, a major decrease in base saturation was observed at Kaboli which was independent of the mulch rate (Table 1 and 8).

DISCUSSION

Mulching Effects in the Sahelian Zone

The large increases in millet TDM following P application from the first year onward provide good evidence of the major role of this mineral nutrient in the Sahel and confirm the additive effects of CR and P application shown previously by Hafner et al. (1993b). The data also show the cumulative effects of CR application with time (Fig. 1). In the first and second year of application, residue-induced increases in millet TDM appeared to

Table 6. Average total dry matter (TDM) yields of cereals with crop residue mulch applied at 500 kg CR ha^{-1} for 4 yr at eight sites in West Africa. Data are averages of 64 replicates across eight phosphorus treatments and four nitrogen treatments, values in brackets are standard errors of the mean.

	TDM			
Site	**1995**	**1996**	**1997**	**1998**
	kg ha^{-1}			
Banizoumbou	**2530 (95)**	**2980 (94)**	**2860 (135)**	**3004 (124)**
Sadoré	**3650 (126)**	**4500 (175)**	**2180 (99)**	**3673 (124)**
Kara Bedji	**3090 (108)**	**3750 (138)**	**3310 (153)**	**3660 (206)**
Goberi	**3570 (151)**	**1980 (71)**	**3120 (125)**	**3520 (235)**
Gaya	**3320 (106)**	**2480 (87)**	**2700 (134)**	**2370 (72)**
Fada	**5930 (134)**	**3190 (75)**	**5140 (152)**	**3180 (106)**
Koukombo	–	**2910 (264)**	**4460 (112)**	**6050 (161)**
Kaboli	–	**3310 (208)**	**3700 (63)**	**4760 (81)**

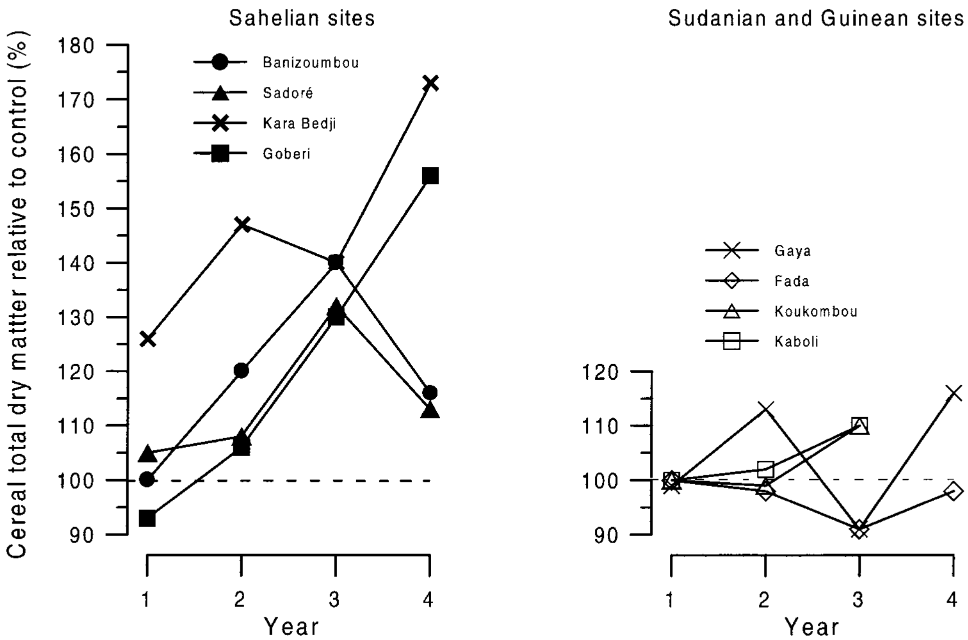

Fig. 5. Total dry matter yield of cereals in plots with an annual application of 2000 kg crop residues (CR) ha^{-1} relative to plots with 500 kg CR ha^{-1}. Data points are means of 64 replicates across eight phosphorus and four nitrogen treatments of an experiment conducted from 1995 to 1998 at four sites in the Sahel, two sites in the Sudanian zone, and two sites in the Guinean zone of West Africa.

be effectively masked by the residual effects of the prolonged fallow leading to a high spatial variability in plant growth. The initially high yields in unmulched plots to which ash has been applied may also be explained by residual effects of former human settlements and trees on some of these plots (Buerkert et al., 1995). Under these typical post-fallow conditions, mulch-induced TDM increases in millet became obvious only in 1993, the third year of application, when TDM production continued to increase at the high mulch rate compared with a rapid TDM decline in unmulched plots (Fig. 1).

While P application led to significant differences in mineral nutrient concentrations within the plants (Buerkert et al., 1998), its effect on nutrient balances was governed by differences in TDM production (Fig. 1). This became particularly obvious for the negative effect of P application on the N and K balances (Fig. 2). However, actual nutrient losses at the village or the watershed level are likely much smaller given the various modes of nutrient recycling via manure in crop- and rangelands as well as wind-related nutrient depositions during fallow periods (Buerkert and Hiernaux, 1998).

The pattern of TDM effects caused by P and CR application points to the interactive mechanisms responsible for the crop growth responses to both factors on sandy Sahelian soils. Phosphorus application strongly increased soil P-Bray across CR levels (Table 4). At the same time, the application of mineral P fertilizer had only minor effects on the more immediate P availability as measured by P-water; however, surface mulched CR increased P-water between 33 and 37% and P-Bray between 20 and 48%, at 0 to 0.2 m, This was most likely due to the small but consistent increase in pH as a result of added basic cations from dust deposition (Stahr and Herrmann, 1996) that was captured in mulched plots and the mobilization of soil P through the release of

Table 7. Effects of millet crop residues (CR) surface mulched for 2 yr at 500 (CR500) and 2000 kg ha^{-1} (CR2000) on soil pH (in 0.01 *M* KCl), water soluble phosphorus (P-water), P-Bray, exchangeable potassium (K), base saturation, and organic carbon (C org) in two depths at two sites in the Sahelian zone of West Africa. Data are means across five P levels.

		pH KCl		P-water		P-Bray		K		Base saturation		C org	
Site	Depth	CR500	CR2000	CR500	CR2000	CR500	CR2000	CR500	CR2000	CR500	CR2000	CR500	CR2000
	m			μg kg^{-1}		mg kg^{-1}		mmol kg^{-1}		%		g kg^{-1}	
Kara	0–0.1	4.21	4.42	464	547	5.3	6.9	0.76	1.03	63	76	1.64	1.70
Bedji	0.1–0.2	4.03	4.12	366	414	2.7	3.2	0.51	0.79	37	45	1.41	1.42
							F-Probability						
	CR	0.002		0.428		0.093		0.002		0.022		0.605	
	P	0.757		0.049		0.005		0.298		0.743		0.766	
	P×CR	0.039		0.181		0.710		0.032		0.028		0.588	
Goberi	0–0.1	4.40	4.57	401	417	6.9	5.9	0.78	1.04	79	88	2.13	2.28
	0.1–0.2	4.15	4.21	283	272	1.7	2.3	0.60	0.72	58	63	1.45	1.46
							F-Probability						
	CR	0.289		0.963		0.769		0.001		0.243		0.258	
	P	0.491		0.111		0.001		0.207		0.615		0.096	
	P×CR	0.310		0.225		0.902		0.167		0.147		0.146	

Table 8. Effects of crop residues (CR) surface mulched for 2 yr at 500 (CR500) and 2000 kg ha^{-1} (CR2000) on soil pH (in 0.01 *M* KCl), water soluble phosphorus (P-water), P-Bray, exchangeable potassium (K), base saturation, and organic carbon (C org) in two depths at two sites in each the Sudanian (Gaya and Fada) and Guinean (Koukombo and Kaboli) zone of West Africa. Data are means across five P levels each applied to two cropping systems.

		pH KCl		P-water		P-Bray		K		Base saturation		C org	
Site	Depth	CR500	CR2000	CR500	CR2000	CR500	CR2000	CR500	CR2000	CR500	CR2000	CR500	CR2000
	m			μg kg^{-1}		mg kg^{-1}		mmol kg^{-1}		%		g kg^{-1}	
Gaya	0–0.1	4.31	4.28	367	247	4.6	5.1	1.24	1.19	76	80	3.62	4.54
	0.1–0.2	3.93	3.95	338	228	0.9	1.3	0.58	0.60	47	49	3.04	3.34
							F-Probability						
	CR	0.870		0.032		0.085		0.711		0.545		0.008	
	P	0.311		0.619		0.001		0.014		0.483		0.013	
	P×CR	0.325		0.175		0.101		0.009		0.070		0.004	
Fada	0–0.1	5.59	5.57	418	324	3.5	2.3	1.51	1.70	99	99	5.10	4.62
	0.1–0.2	5.43	5.54	379	298	2.3	2.1	1.07	1.22	99	99	4.55	4.55
							F-Probability						
	CR	0.619		0.813		0.033		0.085		0.784		0.410	
	P	0.082		0.254		0.015		0.079		0.729		0.556	
	P×CR	0.619		0.292		0.076		0.830		0.537		0.195	
Koukombo	0–0.1	5.50	5.44	1195	1094	6.3	5.6	1.88	1.86	91	95	4.54	4.76
	0.1–0.2	5.45	5.44	1061	939	3.9	3.1	1.39	1.41	94	100	3.82	4.13
							F-Probability						
	CR	0.826		0.371		0.615		0.985		0.045		0.309	
	P	0.445		0.447		0.871		0.919		0.304		0.158	
	P×CR	0.200		0.908		0.062		0.036		0.315		0.077	
Kaboli	0–0.1	4.84	4.97	1077	823	6.1	6.3	2.26	2.56	45	51	6.62	6.65
	0.1–0.2	4.60	4.70	962	668	3.2	2.8	1.28	1.52	44	49	5.73	5.85
							F-Probability						
	CR	0.169		0.037		0.944		0.181		0.320		0.773	
	P	0.019		0.673		0.929		0.198		0.089		0.014	
	P×CR	0.094		0.298		0.559		0.324		0.289		0.406	

organic acids from decomposing CR (Hue, 1991). These acids may have acted as anion exchangers displacing P from the soil matrix and as ligands for Al and Fe (Fig. 6). Compared with the 29 kg P ha^{-1} returned annually with 16 Mg of maize stover in an experiment at IITA (Juo and Lal, 1977), mineralized P from the CR mulch in our study contributed with less than 1 kg P ha^{-1} little to the changes in available P with mulching. To gain a more complete understanding of the dynamic changes of chemical P availability in the different pools, more detailed investigations with isotopic exchange methods are necessary (Frossard et al., 1993).

Mulching is also likely to have improved spatial P availability in the topsoil through increases in root length density as reported by Hafner et al. (1993b). Several interrelated factors may be cited to account for the effects of mulching on root development. These include the combination of small differences in soil moisture leading to higher nutrient availability, a smaller physical resistance to root elongation, and a hormone driven feed-back mechanism stimulating root growth through larger bacterial populations that feed on exudates of larger plants (Buerkert et al., 1995; Hafner et al., 1993a; Kretzschmar et al., 1991; Fig. 6). In most of the trials in the Sahelian zone, mulch application visibly reduced the formation of new surface crusts because of a reduction in wind-induced soil movement (Michels et al., 1995a) and the increase in termite activity observed repeatedly with higher mulch rates.

The large effects of mulching on base saturation in the topsoil of CR plots reflect the increase in pH and cations, particularly K, as a result of released nutrients from decomposing residues and dust deposits (Table 3 and 4). Compared with the 44 kg K from 2000 kg CR ha^{-1}, of which about 85% was decomposed after 12 mo in the Sahel, K inputs from dust deposition are much smaller. For well protected surfaces such as fallow, K inputs from Harmattan winds have been estimated at between 6 and 15 kg K ha^{-1} yr^{-1} (Herrmann et al., 1994).

It may be argued that these mulch-induced changes in nutrient concentration of the topsoil are too small to explain the observed effects on cereal growth. However, the changes are large in relative terms given the fact that the acid Sahelian soils in this study are nothing more than weakly buffered sand cultures. This is supported by Wendt et al. (1993), who found that minor changes in soil parameters, particularly in P availability and in surface crusting, could explain striking differences in plant growth over short distances often referred to as "microvariability" (Brouwer et al., 1993; Buerkert et al., 1996a). The sandy nature of these soils may also explain why CR effects on soil chemical parameters were detected to the 0.8-m depth. The increased C org concentrations in the subsoil and the unexpected changes in P availability below 0.5 m might be caused by increased root growth and leaching of short chain organic molecules from decomposing CR through the profile. This has been hypothesized by Brouwer and Powell (1995), who found large losses of P from a manure trial in a nearby field at Sadoré.

With some differences in the absolute effects of mulching on crop growth and soil parameters, the pattern seems to be remarkably consistent across sites in the Sahel (Fig. 5 and Table 7). The immediate large

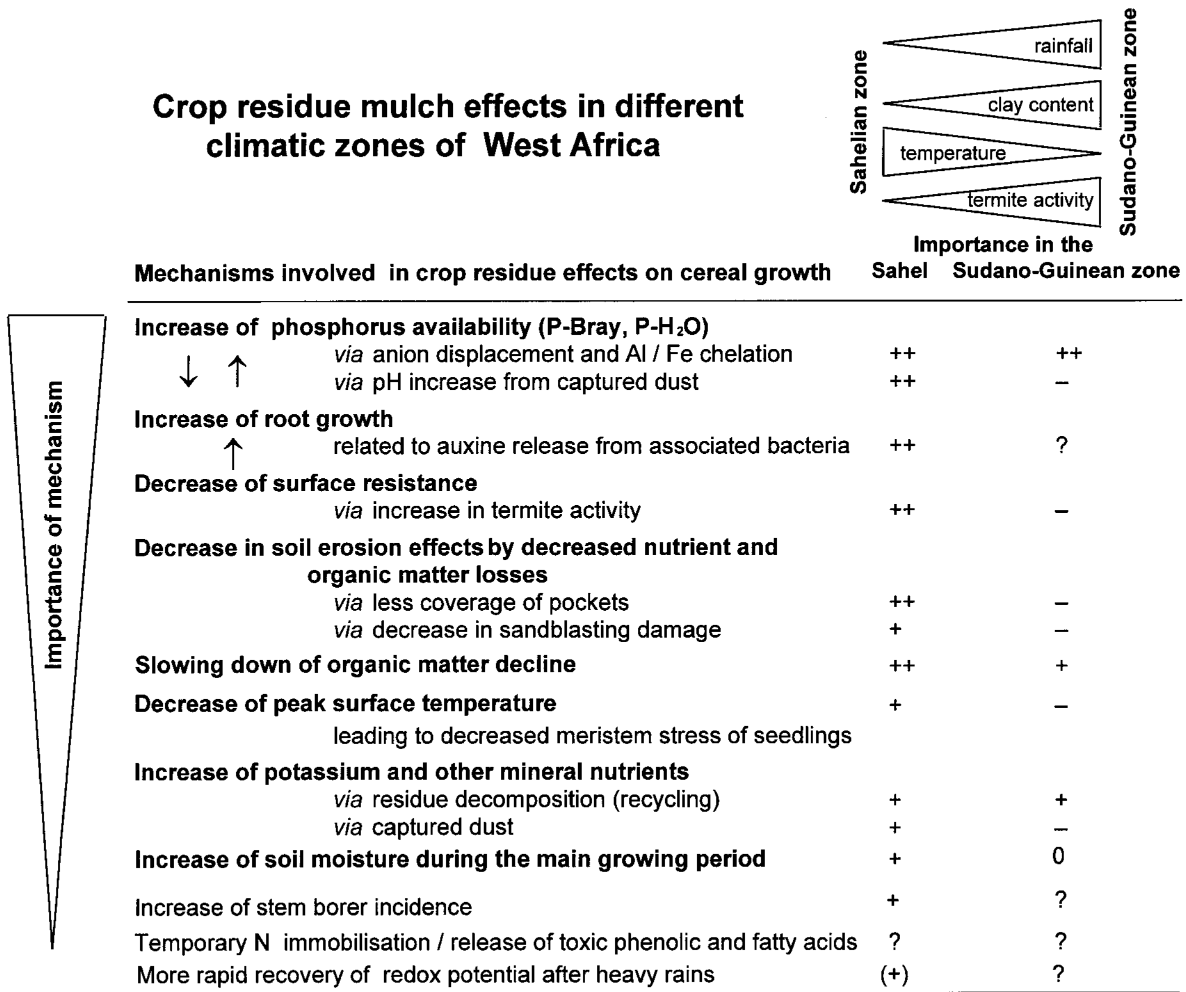

Fig. 6. Conceptual model showing differences in the agro-ecological conditions between the Sahelian and the Sudano-Guinean zone of West Africa and the importance of possible mechanisms involved in crop residue (CR) mulch-induced cereal growth increases. Meaning of symbols are: ++ very important, + important, (+) possibly important, ○ not important, − not relevant, and ? uncertain given insufficient data.

increase of millet TDM with the high mulch rate at Kara Bedji may be due to the fact that, unlike the other sites, the chosen farmer's field had not been left fallow before the establishment of the trial in 1995 but was sown to millet for over five consecutive years.

The significant decrease in soil surface temperature measured in mulched compared with unmulched plots was unexpected given that a mulch rate of 2000 kg ha^{-1} is equivalent to a surface coverage of barely 10%. However, similar temperature differences between unmulched (48.2°C) and mulched plots (41.7°C) have also been measured in an on-farm trial at Maradi, southwestern Niger in 1994 (Buerkert, 1994, unpublished data). The lower soil temperature with mulching may be caused by the combined effects of changes in albedo and surface roughness, increased plant cover, and higher water content at the soil surface. The differences in topsoil temperatures are remarkably similar to those reported from western Nigeria by Lal (1974) and De Vleeschauwer et al. (1978) between unmulched plots and plots with 4 to 6 Mg rice straw ha^{-1}.

The increased water content in mulched plots with higher observed termite activity (Fig. 4) confirms results by Mando et al. (1996) and Mando and van Rheenen (1998) on a Sahelian soil, who measured a 41% higher infiltration and up to 50 mm more stored soil water with termites compared with plots without termites. From their work in Nigeria, De Vleeschauwer et al. (1978) reported up to 11% higher soil moisture storage in the top 0.05 m of a freshly cleared Alfisol due to the application of 6 Mg rice straw ha^{-1}. Under the more humid conditions of their site, this difference was attributed not to termites but to an earthworm-related increased volume of macro-pores and less surface crusting leading to a higher infiltration rate (De Vleeschauwer et al., 1980).

Mulching Effects in the Sudanian and Guinean Zones

Despite slightly higher C org and base saturation in plots with the high mulch rate at most sites (Table 8), the annual application of 2000 kg CR ha^{-1} failed to increase cereal TDM production in the Sudanian and Guinean zone. This was even true in plots that had received yearly applications of 13 kg P ha^{-1} as SSP and

60 or 90 kg N ha^{-1}. To obtain significant effects of mulching on cereal TDM in the more humid zones of West Africa such as the 10 to 29% (Juo and Lal, 1977) and the 50% (Lal, 1974) reported for western Nigeria, mulch rates would likely have to be increased considerably. The latter authors had applied rice straw at rates between 4 and 10 Mg ha^{-1} yr^{-1}. There is little data about residual effects of mulching on crop growth for West Africa that would justify the application of higher mulch rates at intervals. Even for the Sahel with its long dry season and relatively low mineralization rates, the few available reports indicate a substantial decline of mulch effects on millet growth after 1 yr of withdrawal (Rebafka et al., 1994). This is in sharp contrast to large residual effects of straw mulching in the U.S Midwest on corn yield, C org, and N and P availability with a half-life of up to 10 yr (Power et al., 1998).

In view of the mechanisms underlying CR responses in the Sahel (Fig. 6), the results of the soil analyses seem particularly helpful in explaining the striking differences between agro-climatological zones. The minor influence of CR on pH, P-Bray, and particularly P-water at the Sudano-Guinean sites is likely due to (i) less dust deposition, (ii) higher inherent soil fertility and clay contents, (iii) lower air and soil temperatures, (iv) higher rainfall and soil water holding capacity on the heavier soils, and (v) a much higher rate of CR decomposition (Buerkert and Hiernaux, 1998; Fig. 6). While in the Sahel between 15 and 55% of the surface applied 2000 kg CR ha^{-1} remained after 1 yr, in the Sudanian and Guinean zone the complete mulch cover disappeared within 9 to 12 mo. Soil preparation and cultivation methods particular to each zone may also contribute to regional differences in CR mulch effects on soil properties and plant growth. Fields in the Sudanian and Guinean zone are traditionally animal plowed with the first rains before sowing which leads to a mechanical disruption of surface crusts and a partial incorporation of mulch material. Weeding is done with a hand-held hoe which turns the soil to about 0.1 m. In the Sahel, however, millet is typically sown on the untilled soil and fields are weeded with a hand-held metal blade on a long handle that slides on the soil surface at about 0.01 m.

The data of TDM yields at 2000 kg CR ha^{-1} from the eight sites indicate that annual application of mineral N and P fertilizers, the on-farm availability of stover to maintain this mulch rate may be questionable given the multiple competitive uses of CR in the predominant agro-pastoral systems of the region (Table 6; Lamers and Feil, 1993).

CONCLUSIONS

The data support the view that enhanced P availability resulting from residue mulch application is the major cause of subsequent increases in cereal TDM production on weakly buffered acid sandy Sahelian soils. The results also confirm earlier data from western Nigeria that given the strong activity of the soil fauna in the region, mulching can only slow down the decline in C org commonly observed under continuous cultivation, but not increase it.

To predict CR effects on cereal growth across climatic zones, an understanding of the relative importance of the processes involved along the agro-ecological gradient from the Sahel to the Guinean zone is necessary. Nevertheless, it should be stressed that even with substantial inputs of mineral N and P fertilizers, it may remain difficult to obtain crop yields under on-farm conditions which allow the recycling of residues as surface mulch at the often recommended rate of 2000 kg ha^{-1}.

ACKNOWLEDGMENTS

The authors are grateful to A. Moussa, M. Bachir, A. Thiombiano, and I. Oumarou for their technical help at sampling and sample analysis, to H. Traoré (INERA, Burkina Faso) and ICRISAT Sahelian Center for logistical support and to F. Graef for his help with soil classification. They also thank B. Buerkert, B. Gérard, S. Alvey, V. Roemheld, N. van Duivenbooden, E.A. Kirkby, and three anonymous reviewers for their constructive comments on earlier versions of this paper.

REFERENCES

Bationo, A., and A.U. Mokwunye. 1991. The role of manure and crop residues in alleviating soil fertility constraints to crop production: With special reference to the Sahelian and Sudanian zones of West Africa. Fert. Res. 29:117–125.

Bationo, A., B.C. Christianson, W.E. Baethgen, and A.U. Mokwunye. 1992. A farm-level evaluation of nitrogen and phosphorus fertiliser use and planting density for pearl millet production in Niger. Fert. Res. 31:175–184.

Bationo, A., B.C. Christianson, and M.C. Klaij. 1993. The effect of crop residue and fertiliser use on pearl millet yields in Niger. Fert. Res. 34:251–258.

Bationo, A., A. Buerkert, M.P. Sedogo, B.C. Christianson, and A.U. Mokwunye. 1995. A critical review of crop residue use as soil amendment in the West African semi-arid tropics. p. 305–322. *In* J.M. Powell et al. (ed.) Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa. Volume II, Technical Papers. Proceedings of a conference at ILCA, Addis Ababa, Ethiopia. 22–26 Nov. 1993. ILCA, Addis Ababa, Ethiopia.

Brouwer, J., and J.M. Powell. 1995. Soil aspects of nutrient cycling in a manure application experiment in Niger. p. 211–226. *In* J.M. Powell et al. (ed.) Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa. Volume II, Technical Papers. Proceedings of a conference at ILCA, Addis Ababa, Ethiopia. 22–26 Nov. 1993. ILCA, Addis Ababa, Ethiopia.

Brouwer, J., L.K. Fussell, and L. Herrmann. 1993. Soil and crop growth micro-variability in the West African semi-arid tropics: A possible risk-reducing factor for subsistence farmers. Agric. Ecosystems Environ. 45:229–238.

Buerkert, A., C. Haake, M. Ruckwied, and H. Marschner. 1998. Phosphorus application affects the nutritional quality of millet grain in the Sahel. Field Crops Res. 57:223–235.

Buerkert, A., and P. Hiernaux. 1998. Nutrients in the West African Sudano-Sahelian zone: Losses, transfers and role of external inputs. J. Plant Nutr. Soil Sci. 161:365–383.

Buerkert, A., F. Mahler, and H. Marschner. 1996a. Soil productivity management and plant growth in the Sahel: Potential of an aerial monitoring technique. Plant Soil 180:29–38.

Buerkert, A., K. Michels, J.P.A. Lamers, H. Marschner, and A. Bationo. 1996b. Anti-erosive, soil physical and nutritional effects of crop residues. p. 123–138. *In* B. Buerkert et al. (ed.) Wind erosion in Niger. Implications and control measures in a millet-based farming system. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Buerkert, A., and R.D. Stern. 1995. Crop residue and P application affect the spatial variability of non-destructively measured millet growth in the Sahel. Exp. Agric. 31:429–449.

Buerkert, A., R.D. Stern, and H. Marschner. 1995. Post stratification clarifies treatment effects on millet growth in the Sahel. Agron. J. 87:752–761.

De Vleeschauwer, D., R. Lal, and M. De Boodt. 1978. The comparative effects of surface applications of organic mulch versus chemical soil conditioners on physical and chemical properties of the soil and on plant growth. Catena 5:337–349.

De Vleeschauwer, D., R. Lal, and R. Malafa. 1980. Effects of amounts of surface mulch on physical and chemical properties of an alfisol from Nigeria. J. Sci. Food Agric. 31:730–738.

Frossard, E., C. Feller, H. Tiessen, J.W.B. Stewart, J.C. Fardeau, and J.L. Morel. 1993. Can an isotopic method allow for the determination of the phosphate-fixing capacity of soils? Commun. Soil Sci. Plant Anal. 24:367–377.

Gee, G.W., and J.W. Bauder. 1986. Particle size analysis. *In* A. Klute (ed.) Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Gericke, S., and B. Kurmies. 1952. Die kolorimetrische Phosphorsäurebestimmung mit Ammonium-Vandadat-Molybdat und ihre Anwendung in der Pflanzenanalyse. Z. Düngg. Pflanzenernähr. Bodenk. 59:235–247.

Hafner, H., J. Bley, A. Bationo, P. Martin, and H. Marschner. 1993a. Long-term nitrogen balance for pearl millet (*Pennisetum glaucum* L.) in an acid sandy soil of Niger. J. Plant Nutr. Soil Sci. 156:169–176.

Hafner, H., E. George, A. Bationo, and H. Marschner. 1993b. Effect of crop residues on root growth and nutrient acquisition of pearl millet in an acid sandy soil in Niger. Plant Soil 150:117–127.

Herrmann, L., B. Sponholz, and K. Stahr. 1994. Quellregionen für den Harmattan-Staub in Westafrika: Ein mineralogischer und geochemischer Ansatz. Mitteilgn. Dtsch. Bodenkundl. Gesellsch. 74:367–370.

Hoogmoed, W.B., and L. Stroosnijder. 1984. Crust formation on sandy soils in the Sahel. I. Rainfall and infiltration. Soil Tillage Res. 4:5–23.

Hue, N.V. 1991. Effects of organic acids/anions on P sorption and phytoavailability in soils with different mineralogies. Soil. Sci. 152:463–471.

Juo, A.S.R., and R. Lal. 1977. The effect of fallow and continuous cultivation on the chemical and physical properties of an alfisol in western Nigeria. Plant Soil 47:567–584.

Kretzschmar, R.M., H. Hafner, A. Bationo, and H. Marschner. 1991. Long- and short-term effects of crop residues on aluminium toxicity, phosphorus availability and growth of pearl millet in an acid sandy soil. Plant Soil 136:215–223.

Lal, R. 1974. Soil temperature, soil moisture, and maize yield from mulched and unmulched tropical soils. Plant Soil 40:129–143.

Lal, R., D. De Vleeschauwer, and R. Malafa Nganje. 1980. Changes in properties of a newly cleared tropical alfisol as affected by mulching. Soil Sci. Soc. Am. J. 44:827–833.

Lamers, J.P.A., and P. Feil. 1993. The many uses of millet residues. ILEA Newsl. 9(3):15.

Lawes Agricultural Trust. 1993. GENSTAT 5 release 3 reference manual. Oxford University Press, Oxford.

Mando, A., L. Stroosnijder, and L. Brussaard. 1996. Effects of termites on infiltration into crusted soil. Geoderma 74:107–113.

Mando, A., and T. van Rheenen. 1998. Termites and agricultural production in the Sahel: From enemy to friend? Neth. J. Agric. Sci. 46:77–85.

Maurya, P.R., and R. Lal. 1981. Effects of different mulch materials on soil properties and on the root growth and yield of maize (*Zea mays*) and cowpea (*Vigna uniguiculata*). Field Crops Res. 4:33–45.

McLean, E.O. 1982. Soil pH and lime requirement. p. 199–224. *In* A. L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Michels, K., M.V.K. Sivakumar, and B.E. Allison. 1995a. Wind erosion control using crop residue: I. Effects on soil flux and soil properties. Field Crops Res. 40:101–110.

Michels, K., M.V.K. Sivakumar, and B.E. Allison. 1995b. Wind erosion control using crop residue: II. Effects on millet establishment and yield. Field Crops Res. 40:111–118.

Olsen, S.R., and L.E. Sommers. 1982. Phosphorus. p. 403–430. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. Chemical and microbial properties. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Penning de Vries, F.W.T., and H. van Keulen. 1982. La production actuelle et l'action de l'azote et du phosphore, p. 196–226. *In* F.W.T. Penning de Vries and M.A. Djitèye (ed.) La productivité des pâturages sahéliens. Une etude des sols, des végétations et de l'exploitation de cette ressource naturelle. Purdoc, Wageningen, the Netherlands.

Power, J.F., P.T. Koerner, J.W. Doran, and W.W. Wilhelm. 1998. Residual effects of crop residues on grain production and selected soil properties. Soil Sci. Soc. Am. J. 62:1393–1397.

Rebafka, F.-P., A. Hebel, A. Bationo, K. Stahr, and H. Marschner. 1994. 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. Field Crops Res. 36:113–124.

SAS Institute. 1991. SAS Language and procedures: Usage 2. Ver. 6, 1st ed. SAS Institute Inc., Cary, NC.

Sissingh, H.A. 1971. Analytical technique of the Pw method used for the assessment of the phosphate status of arable soils in the Netherlands. Plant Soil 34:483–486.

Stahr, K., and L. Herrmann. 1996. Origin, deposition and composition of dust and consequences for soil and site properties with special reference to the semi-arid regions of West Africa. p. 56–65. *In* B. Buerkert et al. (ed.) Wind Erosion in Niger. Implications and control measures in a millet based farming system. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Stoorvogel, J.J., and E.M.A. Smaling. 1994. Assessment of soil nutrient depletion in sub-Saharan Africa: 1983–2000. Vol. 1. Main Report. DLO - Winand Staring Centre, Wageningen, the Netherlands.

Valentin, C., and L.M. Bresson. 1992. Morphology, genesis and classification of surface crusts in loamy and sandy soils. Geoderma 55:225–245.

Walkley, A., and I.A. Black. 1934. An examination of the Degtjareff methods for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 37:29–38.

Wendt, J., W.A. Berrada, M.G. Gaoh, and D.G. Schulze. 1993. Phosphorus sorption characteristics of productive and unproductive Niger soils. Soil Sci. Soc. Am. J. 57:766–773.

West, L.T., L.P. Wilding, J.K. Landeck, and F.G. Calhoun. 1984. Soil Survey of the ICRISAT Sahelian Center, Niger, West Africa. Texas A&M University/TropSoils, College Station, TX.