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Wind erosion control using crop residue I. Effects on soil flux and soil properties

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Abstract

Effects of millet stover residue (0, 500, and 2000 kg ha^{-1}) on wind erosion and surface soil properties were determined from 1991 to 1993 at the ICRISAT Sahelian Center in Niger, West Africa. Soil flux 0.1 m above the ground was significantly reduced with 2000 kg ha^{-1} residue but not with 500 kg ha^{-1}. Topographic measurements indicated that soil removed from the soil surface was less with either residue level than in the control. After 2 y, the soil surface (0–0.01 m) of both residue treatments had less coarse sand than the control, but more fine sand and clay, more organic carbon and an increased cation exchange capacity. The organic-C content of blown material was greater than that of surface soil. An amount of 500 kg ha^{-1} residue can be considered useful for soil conservation, but 2000 kg ha^{-1} are required for a significant reduction of soil flux caused during severe wind erosion events.

Keywords: Erosion control; Soil properties

1. Introduction

Wind erosion affects soil productivity and causes crop damage worldwide. Dregne (1990) reported that wind erosion has reduced long-term soil productivity by more than 50% in parts of southeast Tunisia. Dregne (1992) indicated, however, that it is not yet clear if short-term effects of wind erosion on soils and crops are more serious than long-term productivity losses. On the other hand, eolian deposits provide useful inputs of K, Ca, and Mg for the chemically poor soils of the Sahel (Herrmann et al., 1994), but they also increase the formation of surface crusts.

Wind erosion in the Southern Sahelian Zone (SSZ) of West Africa is a well-known and widespread phenomenon. In the colonial period, Aubert et al. (1947) reported that northeastern winds caused erosion during the dry season from November to April in Mali and Senegal. The susceptibility of the soils to erosion by wind was reinforced by decreasing vegetative cover and by disturbances through cattle tracks. Raulin (1965) noticed the removal of a thin fertile top layer by wind erosion in Niger. A first approach to quantify microtopographic changes due to wind erosion in Chad was reported by Guichard and Marius (1961). Coudé-Gaussen et al. (1993) presented an approach to map the wind erosion risk in the Sahel region by combining remote sensing with data of soil parameters and vegetative cover. During the 1990 rainy season, 21 wind erosion events were observed at the ICRISAT Sahelian

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Center (ISC) in southwest Niger, with a total annual soil flux of 1260 kg m^{-2} of sampler opening at 0.1 m above the ground (Michels et al., 1993). Beside the susceptibility to wind erosion, sloping areas may be also subject to water erosion during intense rain, and those effects on soils and their productivity in the SSZ should not be underestimated (Delwaulle, 1973; Casenave and Valentin, 1989; Geiger and Manu, 1993).

Wind erosion control measures should be regarded within the context of resource availability for the farming systems. In the millet-based production systems of the Sahel region, generally few external inputs are used by farmers. Soil enrichment by green manuring, increased vegetated fallow periods, and windbreaks of natural vegetation have been recommended as control measures (Aubert et al., 1947; Aubert, 1948). Some farmers in Niger use residues of millet to reduce wind erosion damages (Raulin, 1965; Taylor-Powell et al., 1991). Wind tunnel measurements have shown the effectiveness of soil cover to reduce wind erosion (Lyles and Allison, 1975; Fryrear, 1985). Field data on the effects of different millet straw amounts on wind erosion and soil characteristics, however, are scarce. The objective of this study was to measure wind erosion in a millet field with different levels of stover, and to determine effects on physical and chemical properties of windblown material and of surface soil. The effects on crop production are reported in a second paper (Michels et al., 1995).

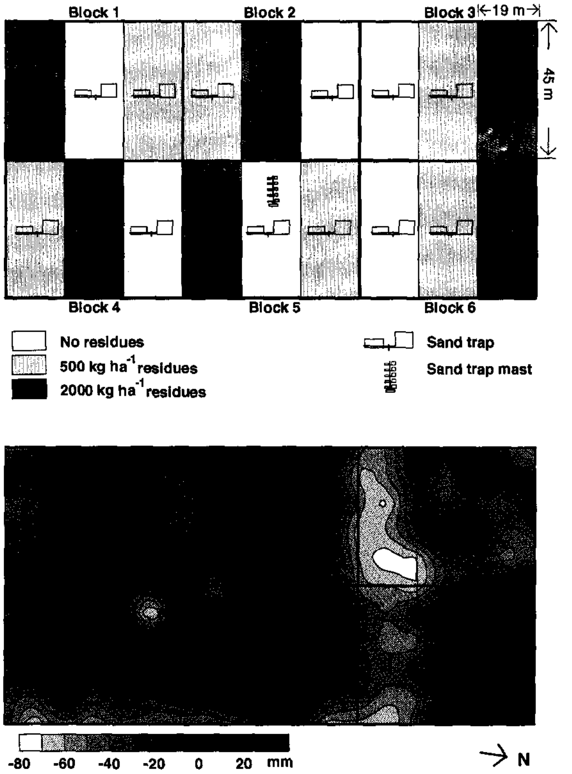

Fig. 1. Experimental layout (cross-over design) of the crop residue trial at the ICRISAT Sahelian Center (top), and relative changes in topography after 1 y of residue application, in mm (bottom).

2. Materials and methods

2.1. Site and experimental layout

Measurements were done from May 1991 through April 1993 at the ICRISAT Sahelian Center (ISC), situated in the southwestern part of Niger (13°15′N, 2°18′E, 240 m alt.). Rainfall events, occurring from May to September, are regularly preceded by short eastern sand storms, whereas a northeastern wind ("Harmattan") transports dust from the Sahara during the dry season from October to April. The soil at the experimental site is classified as a (sandy, siliceous, isohyperthermic) Psammentic Paleustalf of the Labucheri soil series (West et al., 1984), according to the US Soil Taxonomy. The 0–0.1-m layer has 91% sand, 6% silt, 3% clay and pH (KCl) 4.9. Native fertility is low, with 2.8 mg kg^{-1} available P (Bray-1), 10 mmol kg^{-1} cation exchange capacity (NaOAC), and 2 g kg^{-1} organic carbon content. A laterite gravel was encountered at depths of 3 to more than 6 m. There was a 0.9% slope in the field from SE to NW.

Standing millet residue, weeds and wild-grown shrubs had been removed manually from a field 1.5 ha in size. Prior to the onset of each rainy and dry season, millet residue amounts of 500 kg ha^{-1} and 2000 kg ha^{-1} were distributed on the soil surface. Residues remaining after the preceding growing season were used on the plots where they had grown, and complemented to the amount required with straw from other fields at ISC, if necessary. One treatment without any residues served as control. The treatments were arranged in a spatial cross-over design with three factor levels and six replications, with a plot size of 19×45 m (Fig. 1). It was unclear if treatments on the eastern field part would influence the effects of those on the western part. Thus, three of the replicates were on the western field part and three on the eastern with the treatments arranged in a predetermined topographical sequence. This design enabled us to detect possible carry-over effects of a specific treatment on the eastern side on any treatment on the western side. We visually estimated the percent soil cover by 2000 kg ha^{-1} residue to be around 7%. Amounts of 2000 kg ha^{-1} millet straw contain 15 to 23 kg N and about 1 kg P (Powell and Fussell, 1993). In all plots, millet was sown in pockets on a 1×1 m grid at the onset of both rainy seasons as described by Michels et al. (1995).

2.2. *Wind erosion parameters*

Wind speed at 2 m height was measured with a A100R cup anemometer (Vector Instruments, North Wales) at the ISC weather station, situated 1 km west of the field. Hourly averages of wind speeds at 2 m height and time and duration of rainfall events were recorded with a CM10 automatic weather station and stored on a CR10 data logger (Campbell Scientific, Shepshed, UK). During the 1992 rainy season, wind speeds above 6 m s^{-1} at 2 m height were recorded in averages per minute. Skidmore and Tatarko (1990) used 8 m s^{-1} at the 10 m height as threshold wind speed to initiate erosion from an unprotected surface of highly erodible particles. According to those authors, a 6 m s^{-1} velocity at 2 m above the ground corresponds to 7.6 m s^{-1} at 10 m height. Erosive wind power was calculated for the 1992 storms using Eq. 1.

$$WE = 60\rho\sum_{i=1}^{n}(u_i^2 - u_t^2)^{3/2} \qquad (1)$$

where WE is the specific wind power (W m^{-2}) exceeding threshold windspeed at 10 m height (u_t, m s^{-1}), 60 is for the number of seconds per one-minute observation, ρ is air density (kg m^{-3}), n is the number of observations with $u_i > u_t$ (storm duration, in min) and u_i is the ith observed wind speed (m s^{-1}) at 10 m height. For the calculation of the erosive wind power, wind speeds were adjusted to 10 m height and a threshold of 8 m s^{-1} was used (Skidmore and Tatarko, 1990). Observations after the starting of rainfall were omitted.

A BSNE dust sampler (Fryrear, 1986) was installed in the middle of each plot at 0.1 m above the soil surface (Fig. 1). The vertical sampler opening was 20 mm wide and 50 mm high, thus sampling a range from 0.075 to 0.125 m above the soil surface. Additionally, a mast was installed with sampler heights of 0.1, 0.35, 0.50, 0.75 and 1.0 m in a control plot in the middle of the field. After each erosion event during the rainy seasons, and twice per month during the dry seasons, the eroded soil collected in each sampler was washed onto a No. 44 Whatman filter paper (Whatman International, Maidstone, UK). The filter paper was oven-dried at 110°C for 48 h and weighed. One storm on 20 May 1991 was not sampled and no sampling was done in November 1991 and 1992.

Topographical measurements were done on a 9×9 m grid in November 1991 and November 1992 using a theodolite. In each year, the lowest grid mark on the field was used as reference height and adjusted to 0 m. Changes in surface elevation within that time period were obtained by calculating the relative height differences between both observation dates for each point. Figures from the border lines between two treatments were omitted for the calculation of treatment effects, and only the four measurement points within the treatment plots were used.

2.3. *Properties of surface soil and of windblown material*

Soil samples were taken from the surface (0–0.01 m depth) of each plot in November 1992. The particle size distribution and chemical properties were analyzed for these samples and for blown soil collected with the central mast during the rainy-season erosion events. Samples were air-dried and sieved to pass a 2-mm screen. Grain-size distributions were analyzed in a constant temperature room. A 10- to 20-g sample was dispersed in 0.05 *N* NH_4OH and mixed using an oscillating shaker for 12 h. Sand fractions (2000 to 63 μm) were then measured by sieving. Silt and clay fractions (<63 μm) were determined by collecting aliquots with a pipette in 0.1 m depth, after appropriate settling times in 1000 ml water (Schlichting and Blume, 1966). Soil chemical analyses were done for pH (1:2 KCl), organic carbon (Walkley and Black, 1934), available phosphorus (Bray-1 procedure; Olsen and Sommers, 1982), and for the exchangeable bases as follows: concentrations of Ca and Mg were measured by atomic adsorption, and Na and K by flame emission spectrophotometry, after extraction with 1 *N* ammonium acetate. Exchangeable Al and H^+ were determined according to McLean (1982). The effective cation exchange capacity (ECEC) was calculated as the sum of exchangeable bases and exchangeable acidity.

2.4. Data analysis

Analyses of variance were performed using the general linear model (LM) procedure of the SAS software (SAS Institute, 1988). Owing to the cross-over design, a factor "field part" was included in the statistical model for each measured parameter. If it was indicated significant, a two-degree-of-freedom contrast was used to detect a specific carry-over effect λ_i (where i equals the residue amount, 0, 500, or 2000 kg ha^{-1}), i.e. to learn whether λ_0, λ_{500}, and λ_{2000} were different from each other. When a lingering effect from eastern-side treatments interfered with the response of those on the western side (residual effect), data from the western side were omitted from the specific analysis (Milliken and Johnson, 1984). This occurred only for sand flux data on 24 May and 1 June 1992. The grid for the topographic map was calculated using the Surfer software, V. 5.00 (Golden Software, Golden, Colorado). A probability level of $P<0.1$ was used in all F-tests to indicate significant treatment effects; Fisher's Protected LSD was applied for comparisons of means.

3. Results

3.1. Wind erosion

Twelve erosion storms were measured between May and the beginning of August in each of the 1991 and 1992 rainy seasons (Table 1). One of the highest sand fluxes was measured on 27 July 1992 when the millet crop had exceeded 1 m height. During the Harmattan season 1991/92, highest wind speeds were measured in December and January, but in 1992/93 they occurred mainly during March and April (Table 2). Maximum wind speed at 2 m height during rainy season storms was 8.2 m s^{-1} (hourly average) in 1991 and 19.6 m s^{-1} (average per minute) in 1992, and was thus higher than in the Harmattan period. The storm duration with wind speeds exceeding 6 m s^{-1} at 2 m height was between 3 min and less than an hour in 1992. In 16 of 24 erosion events, rainfall occurred the same day and started before or within 30 min after the high winds began (Table 1). Rains preceding high wind speeds prevented soil erosion on 25 May and 31 July 1992. The storm on 1 June 1992 was the only event when some residue cover was blown within or away from the plots. In that case, new residues were applied to provide similar conditions for the subsequent storms. The correlation between soil flux in the control plots and the calculated erosive wind energy was poor (Table 1).

The application of 2000 kg of residue ha^{-1} reduced soil flux significantly in 10 out of 12 storms in 1991 and in 7 out of 12 storm events in 1992. Total soil flux during the rainy season storms was 46% less with 2000 kg ha^{-1} residue than in the control in 1991 and 48% less in 1992. No significant difference in soil flux between the 500 kg ha^{-1} treatment and the control was obtained in either rainy seasons, except for the first storm in 1992 (6 May) when 500 kg ha^{-1} reduced soil flux significantly by 34%. The total dry season soil flux 1991/92 was more than double that of the 1992/93 dry period, but did not exceed 175 kg m^{-2} of the vertical sampler opening (Table 2). The application of 500 kg residue ha^{-1} resulted in an averaged 53% reduction of total soil flux during both dry seasons, whereas 2000 kg ha^{-1} decreased soil flux by 92%.

Topographic measurements indicated a high variability of soil displacements within the whole field and within plots. There were losses at the eastern field edge from November 1991 to November 1992, but gains on the western edge, irrespective of treatments (Fig. 1). Highest losses occurred on the two adjacent control plots of blocks 3 and 6. When the induced height differences within the 1-y period were averaged over treatments, relative decreases of the 500 and 2000 kg ha^{-1} treatments were 18 and 16 mm less, respectively, than of the control plots. These figures only show relationships among treatments and should not been used to calculate soil losses from the field.

3.2. Properties of surface soil and of windblown material

The particle size distribution of the top soil layer (0–0.01 m) after 2 y of residue application was significantly affected by the amounts of residue employed (Table 3). The coarse sand fraction (2000–630 μm) was less for both residue levels compared to the control. The fine sand fraction (200–63 μm) and clay content (<2 μm) were greater with both residue levels than

Table 1
Storm-related wind erosion data of the 1991 and 1992 rainy season at ISC, Sadoré, Niger

Date	DAE	Wind storms						Soil flux ($kg\ m^{-2}$)			ANOVA for soil flux		
		Time (h)	Duration (>6 $m\ s^{-1}$) (min)	Speed max ($m\ s^{-1}$)	Onset of rain (h)	Amount of rain (mm)	Wind power[a] ($kJ\ m^{-2}$)	Crop residues ($kg\ ha^{-1}$)			$P>F$	$LSD_{0.1}$ ($kg\ m^{-2}$)	CV (%)
								0	500	2000			
1991													
1 June	3	about 02.00	n.a.	8.2	01.09	13	n.a.	169	192	58	0.014	68	46
3 June	5	about 03.00	n.a.	7.6	–	0	n.a.	279	293	174	0.102	97	37
7 June	9	about 05.00	n.a.	5.9	12.05	13	n.a.	57	79	40	0.098	29	46
11 June	13	about 23.00	n.a.	7.4	23.06	1	n.a.	216	219	83	0.010	70	38
15 June	17	about 10.00	n.a.	3.7	07.04	10	n.a.	10	11	3	0.021	5	53
21 June	23	about 01.00	n.a.	6.6	00.26	9	n.a.	24	24	6	<0.001	6	31
22 June	25	about 23.00	n.a.	7.5	05.27	2	n.a.	240	229	138	0.034	64	29
26 June	29	about 24.00	n.a.	7.9	22.52	38	n.a.	109	91	60	0.034	28	30
8 July	40	about 12.00	n.a.	6.2	–	0	n.a.	81	76	57	0.001	8	10
14 July	46	about 09.00	n.a.	7.3	–	0	n.a.	<1	<1	<1	–	–	–
17 July	49	about 12.00	n.a.	5.2	–	0	n.a.	11	31	18	0.014	9	44
25 July	57	about 18.00	n.a.	5.0	08.00	35	n.a.	30	40	19	0.025	11	35
4 Aug	66	about 01.00	n.a.	5.6	23.32, 3 Aug	58	n.a.	12	12	11	0.870	2	20
Total								1238	1297	667	<0.001	186	16
1992													
6 May		n.a.	n.a.	n.a.	–	0	n.a.	136	90	27	0.004	41	45
12 May		17.52–18.27	9	7.0	17.58	1	4	38	32	4	0.025	20	73
24 May		16.11–17.07	7	9.5	–	0	221	53	31	20	0.464	52	85
25 May		16.13–16.17	3	6.7	15.49	19	0	<1	<1	<1	–	–	–
28 May		17.44–18.05	16	13.6	18.04	4	848	73	75	40	<0.001	12	17
1 June	2	18.32–19.41	57	19.6	18.50	29	7922	302	369	67	0.043	173	40
4 June	5	22.16–23.20	37	11.3	23.10	9	665	179	232	192	0.490	85	39
13 June	14	00.53–01.35	11	7.8	01.41	9	23	–	–	–	–	–	–
14 June	15	04.12–04.24	7	7.2	–	0	259	166[b]	170	100	0.114	57	39
20 June	21	06.32–07.13	37	8.9	06.57	17	289	49	35	25	0.235	23	60
24 June	25	–	0	5.8	–	0	0	43	39	7	0.030	22	70
2 July	33	11.41–12.09	25	10.3	–	0	5407	88	83	78	0.850	39	37
18 July	49	02.25–03.40	47	8.1	02.39	27	30	69	64	44	0.085	19	30
27 July	58	17.29–17.47	18	9.7	17.41	11	152	287	252	167	0.038	72	29
31 July	62	15.51–18.25	34	13.3	13.50	75	0	<1	<1	<1	–	–	–
Total								1483	1473	772	0.001	267	19

[a]Specific wind power for wind speeds exceeding 8 $m\ s^{-1}$ at 10 m height; observations after the beginning of rain were excluded.
[b]Samples from 13 and 14 June 1992 were collected together.
n.a., data not available.

the control. Furthermore, there were significant changes in the soil chemical properties of the soil surface material. The 2000 $kg\ ha^{-1}$ treatment had higher pH, ECEC, and organic-C content than the control (Table 4). The 500 $kg\ ha^{-1}$ residue treatment was not significantly different from the control, except for ECEC. There were no differences in Bray-P contents among treatments.

Blown material captured at different heights during both rainy seasons in the control plot had grain size distributions that were clearly affected by height above the surface (Table 3). The percentage of medium coarse sand (630–200 μm) decreased with measurement height whereas the amounts of fine sand (200–63 μm) and coarse silt (63–20 μm) increased with height above the soil surface. The clay content at 0.75 m height was increased compared to lower heights. When comparing grain size distributions of the soil surface with those from material captured at different heights, the blown material had more clay, coarse silt and fine sand than the surface material of the control plot. When chemical properties of captured material

Table 2
Wind erosion data of the 1991/92 and 1992/93 Harmattan seasons at ISC, Sadoré, Niger

Time period	Wind parameter			Soil flux (kg m²)			ANOVA		
	Speed max. ($m s^{-1}$)	Date	Hour	Residue ($kg ha^{-1}$)			$P>F$	$LSD_{0.1}$ ($kg m^{-2}$)	CV (%)
				0	500	2000			
1991/92									
1–15 Dec	5.6	15 Dec	11.00	33.9	15.7	1.3	0.010	14.7	81
16–31 Dec	5.9	31 Dec	11.00	60.1	20.5	5.3	0.106	44.5	140
1–15 Jan	5.8	6 Jan	11.00	45.4	22.6	6.6	0.045	23.7	89
16–31 Jan	7.3	24 Jan	14.00	35.3	18.0	6.0	0.350	36.5	167
Feb	6.8	14 Feb	12.00	<1	<1	<1	–	–	–
Mar	6.2	20 Mar	12.00	<1	<1	<1	–	–	–
Apr	8.3	10 Apr	22.00	<1	<1	<1	–	–	–
Total				175	77	19	0.082	111	115
1992/93									
1–15 Dec	5.0	1 Dec	10.00	0.3	0.2	0.2	0.430	0.1	56
16–31 Dec	5.1	24 Dec	10.00	0.2	0.1	0.1	0.078	0.1	45
1–15 Jan	6.5	11 Jan	11.00	6.0	1.0	0.2	<0.001	1.4	55
16–31 Jan	5.6	20 Jan	11.00	0.5	0.2	0.2	<0.001	0.1	32
1–15 Feb	6.8	8 Feb	11.00	2.4	1.1	0.3	0.007	0.9	66
15–28 Feb	5.8	18 Feb	01.00	0.9	0.4	0.3	0.107	0.6	102
1–15 Mar	5.9	5 Mar	11.00	1.0	1.2	0.2	0.029	0.6	69
16–31 Mar	7.1	25 Mar	11.00	26.0	8.7	1.2	<0.001	5.2	40
1–15 Apr	5.5	10 Apr	15.00	14.6	10.3	1.4	0.014	6.4	68
16–30 Apr	4.5	27 Apr	16.00	20.2	11.9	0.7	<0.001	5.1	44

Table 3
Particlesize distribution of soil surface layer (0–0.01 m depth) after 2 y of crop residue application, and of eolian material captured at different heights above the surface during the 1991 and 1992 rainy season, ISC, Sadoré, Niger

	Particle size distribution (% of total content)							Geometric mean diameter (mm)	Geometric standard deviation
	2000–630	630–200	200–63	63–20	20–6.3	6.3–2	<2 (μm)		
Residues ($kg ha^{-1}$)									
0	11.2	57.0	27.0	2.1	0.5	0.7	1.5	0.829	3.12
500	8.1	55.9	30.9	2.7	0.2	0.3	1.8	0.815	3.32
2000	4.4	53.6	36.4	2.4	0.7	0.6	1.8	0.801	3.43
$LSD_{0.1}$	2.5	4.0	4.3	1.6	0.6	0.6	<0.1	–	–
Soil catch 1991[a]									
0.10 m	1.7	56.0	36.8	2.8	0.0	0.9	1.9	0.796	3.50
0.35 m	1.7	49.2	44.1	2.8	0.1	0.5	1.7	0.815	3.29
0.50 m	0.6	43.0	49.1	4.7	0.5	0.3	1.8	0.753	3.81
0.75 m	1.3	43.0	48.5	3.6	0.1	0.4	3.1	0.722	4.54
Soil catch 1992[a]									
0.10 m	0.8	41.6	49.1	5.8	0.6	0.2	1.9	0.720	4.13
0.35 m	4.5	37.6	45.3	9.0	0.9	0.5	2.3	0.614	5.34
0.50 m	2.8	22.9	59.2	11.7	0.4	1.0	2.1	0.567	5.83
0.75 m	1.6	10.4	62.7	18.1	2.6	0.3	4.3	0.370	10.46
ANOVA ($P>F$)									
Residue	0.032	0.258	0.009	0.742	0.314	0.475	0.052	–	–
CV (%)	28	6	12	56	111	95	13	–	–

[a]Material caught at 1 m height was not sufficient for analysis.

Table 4
Chemical properties of soil surface layer (0–0.01 m depth) after 2 y of crop residue application, and of eolian material captured at two heights above the surface during the 1992 rainy season, ISC, Sadoré, Niger

	pH (KCl)	Organic-C ($g\ kg^{-1}$)	Bray-1 P ($mg\ kg^{-1}$)	Exchangeable cations ($mmol\ kg^{-1}$)						ECEC ($mmol\ kg^{-1}$)
				H^+	Al^{3+}	Na^+	K^+	Ca^{2+}	Mg^{2+}	
Residues ($kg\ ha^{-1}$)										
0	4.7	1.16	14	0.2	0.4	1.1	0.4	4.6	1.8	8.5
500	4.7	1.22	14	0.2	0.3	1.1	0.5	5.3	1.7	9.2
2000	5.0	1.62	14	0.2	0.1	1.1	0.7	5.9	2.2	10.0
$LSD_{0.1}$	0.2	0.29	3	<0.1	0.2	<0.1	0.2	0.6	0.2	0.7
Soil catch 1992										
0.10 m	5.1	1.51	27.8	0.4	0.2	1.2	0.4	7.4	1.9	11.5
0.35 m	n.a.	2.03	25.4	n.a.	n.a.	1.4	0.4	9.0	2.0	>13.1
ANOVA ($P>F$)										
Residue	0.050	0.033	0.984	0.153	0.129	0.095	0.117	0.010	0.005	0.004
CV (%)	4	18	21	23	58	2	39	10	9	7

n.a., data not available.

were compared to surface soil, we found higher pH, organic-C content, Bray-P and ECEC in the blown material (Table 4).

4. Discussion

4.1. Wind erosion

Several factors may have influenced the poor correlation between soil flux and the calculated specific erosive wind power. The threshold wind speed employed was derived from the literature and not measured in situ. Furthermore, the soil moisture status at the surface could not be taken into consideration. Skidmore (1986) reported an excellent correlation between mass flow rate and wind power derived from wind tunnel data. He proposed the calculation of a physically based wind-erosion climatic factor that included not only wind power, but also the cohesive resistance caused by water on soil particles. It appears worthy to test if that model fits also for short wind erosion events in the SSZ.

Total soil flux at 0.1 m height in the control plots during the 1991 rainy season was similar to that reported by Michels et al. (1993) for the 1990 growing season on the same field (1261 kg m^{-2} of sampler opening), but in 1992 it was 18% larger. The large sand flux on 27 July 1992 occurred even though the millet crop was in the booting stage. The Leaf Area Index at that time, however, was not more than 1 and thus insufficient to protect the soil surface. Farmers in the region usually have lower planting densities than in our trial, but soil cover is increased by intercropped cowpea and also by weeds. Total soil flux during both Harmattan periods did not exceed the amount eroded during an average storm during the rainy season.

Only the 2000 kg ha^{-1} residue amount reduced the soil movement at 0.1 m height effectively during the storms of the rainy seasons, whereas 500 kg ha^{-1} had no effect. The reduction in soil flux by the 500 kg ha^{-1} residue treatment during the Harmattan seasons was due primarily to lower wind speeds compared to rainy season storms. When wind speed is low, even small obstacles can reduce the actual wind speed near the soil surface below the threshold necessary for soil movement. On the other hand, the different effectiveness may indicate different vertical distribution modes of blown material during the short storms of the rainy season compared to those during the Harmattan period. In storms during the rainy season with higher maximum wind speeds, relatively more material was probably lifted higher above the soil surface and thus captured in the samplers, whereas during the less severe Harmattan events most of the material moved very close to the soil surface and was not captured. A surface-creep sampler, collecting material just above the soil surface, could provide additional information.

A soil-loss ratio SLR (soil loss from covered soil ÷ soil loss from bare flat soil) can be used to describe the effectiveness of residue to reduce wind erosion. Fryrear (1985) calculated a SLR of 0.88 for a 10% soil cover from a combined evaluation of wind-tunnel and field measurements. A formula proposed by Bilbro and Fryrear (1994) yielded a SLR of 0.74 for 7% soil cover. Our measurements of soil flux and topography indicated a higher efficiency of residue cover in reducing wind erosion (SLR of a 7% soil cover ≈ 0.5). Reductions in soil flux were higher in less severe erosion events. Thus, severity and duration of sand storms may be principal determinants of residue effectiveness for soil conservation. It was found that any orientation of residue with respect to the soil surface decreases wind erosion more than the flattened position (Siddoway et al., 1965). Thus, for wind erosion control purposes, standing stubble should be left in the field instead of cutting down the stems. However, densities of millet pockets used in Niger (0.3 to 1.5 m^{-2}) may be too small to provide efficient soil conservation (Lyles and Allison, 1975). In addition, crop residues are used in the SSZ for animal feed, fuel, and construction purposes, amounts of 2000 kg ha^{-1} cannot be expected on fields of peasant farmers without changes in management strategies and without fertilizer application.

The topographic measurements indicated that there was both a redistribution of soil mass within the field and probably losses from the field. One should interpret the figures with caution, as they do not represent absolute values. It is evident, however, that even the smaller amount of residue had a similar effect as the 2000 kg ha^{-1} residue treatment. Geiger et al. (1992) reported that retaining millet stalks and leaves from the previous year on the soil surface provided not only protection for the soil against erosion but entrapped windblown material. Those authors found that the surfaces of the residue plots were 0.15 to 0.2 m higher than the surfaces of nonresidue plots after 5 y. Displacements by wind or water erosion within a field increase the microvariability of soil properties and create less productive and more productive areas within small distances (Scott-Wendt et al., 1988).

The discrepancy between our horizontal flux data and the topographical measurements for the 500 kg ha^{-1} residue treatment stress difficulties with the methods used. Sand traps and topographic measurements should both be used to interpret wind erosion data. Different results from catchers with vertical openings compared to soil height measurements were also reported by Wilson and Cooke (1980). In order to calculate a mass and nutrient balance for a wind-erosion-affected field, the amounts deposited, eroded or leached, need to be determined and analyzed. Research on the effects of removed topsoil on long-term crop yields on the sandy soils is necessary. A holistic wind erosion model should further include the decomposition of residue and the influence of vegetation canopies on turbulence, momentum transfer (Holland et al., 1991; Raupach, 1991) and threshold friction velocities for soil movement (Musick and Gillette, 1990). An approach for the calculation of an erosion-reduction factor for a vegetated surface was presented by Bilbro (1992).

4.2. Properties of surface soil and of windblown material

The higher content of coarse sand in the surface soil of the control plots compared to the residue treatments indicated a residual accumulation of that size fraction. The control plots had the smallest concentration of the 200 to 63 μm soil particles left in the field. The figures for fractions smaller than 63 μm were probably disturbed by crust formation within parts of some plots. It remains unclear from the data presented, however, whether the suspended finer particles were eventually removed during wind storms, or if they were carried back to the field by subsequent rainfalls. Herrmann et al. (1994) measured up to 1.9 t ha^{-1} dust deposition on fallow vegetation during 1992 in Niger. They found furthermore that more material was deposited during the rainy season than during the dry period.

The results for soil chemical properties with different amounts of residue were similar to the findings of Geiger et al. (1992). Those authors found that soil pH, Ca, Mg, K and Bray-1 P contents increased significantly in the top 0.2 m of the soil profile after 5 y of residue application, while organic carbon remained unchanged. We found less organic carbon in the control than with 2000 kg ha^{-1} residue. A loss of organic matter and fine soil particles in the sandy soils would further diminish their water-holding capacity and decrease ECEC. We do not have sufficient data to determine if nutrient accumulation in the soils of residue plots was caused more by decomposed straw or by trapped windblown material.

The trends found in the particle-size distribution of soil material trapped at different heights agreed with findings in other studies. It is well known that suspended particles can range in size from about 2 to 100 μm, and particles larger than 0.8 mm in diameter are considered as non-erodible (Chepil, 1957). In the US Great Plains region, the sand fraction in windblown material decreased with increasing height whereas the silt and clay fractions increased (Zobeck and Fryrear, 1986a). Windblown soil in India had higher contents of the 100 to 250 μm fraction than the field soil (Gupta et al., 1981). In Botswana, however, sand content of blown material was greater than that of soil in the field whereas silt and clay contents were less (Sekhwela, 1992). Geiger et al. (1992) found less clay in the top 0.2 m soil of residue plots than in controls, which could not be fully explained. Zobeck and Fryrear (1986a) reported that the portion of sand increased as sample mass increased, which resulted from the higher wind energy levels associated with the more severe storms. Those authors found no differences in particle size distributions of material collected at 1 m and 2 m above the soil surface. Our data of increasing ECEC and organic carbon concentrations with increasing height agree with those reported from Zobeck and Fryrear (1986b) while the high enrichment ratio for Bray-P and Ca may have resulted from blown fertilizer.

5. Conclusions

The surface application of straw in a millet field in the SSZ reduced the removal and redistribution of topsoil within a field. Amounts of 2000 kg ha^{-1} residue decreased the soil flux 0.1 m above the ground significantly and provided good protection against soil removal. Amounts of 500 kg ha^{-1} decreased the soil flux at 0.1 m height only during less severe events of the Harmattan season, but relative soil removal from the surface was similar to the high straw level. Amounts of 2000 kg ha^{-1} cannot be expected on fields of peasant farmers in the region without changes in management strategies and without fertilizer application, for crop residues are used for animal feed, fuel, and construction purposes. Because wind erosion occurred even in established millet crops, increased biomass production is indispensable for soil conservation in wind-erosion affected areas. Effects of top soil loss on long-term crop production need to be investigated.

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