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Wind erosion control using crop residue II. Effects on millet establishment and yields

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Abstract

Effects of three levels of millet stover residue (0, 500, and 2000 kg ha^{-1}) on establishment and growth of pearl millet (*Pennisetum glaucum* (L.) R.Br) were determined in a wind-erosion-affected area in Niger, West Africa, during 1991 and 1992. The extent of millet seedlings buried by blown soil in plots with 500 kg ha^{-1} residues was similar to that of control plots. A residue amount of 2000 kg ha^{-1} reduced the extent of covered millet, but did not provide complete protection during severe sand storms. Partial covering of millet seedlings by blown soil decreased biomass yields compared to uncovered millet. Grain production, averaged over two years, was about 500 kg ha^{-1} for the control, 570 kg ha^{-1} with 500 kg ha^{-1} residue, and 730 kg ha^{-1} with 2000 kg ha^{-1} residue. Increased yields were caused by both wind erosion protection and direct growth stimulating effects of residue. Stover yields for all treatments in both years were less than 2000 kg ha^{-1} and thus insufficient to sustain the levels required for protection of crops against wind erosion damages. An increase in dry matter left in the field or the implementation of alternative wind erosion control measures is needed for sustainable crop production in wind-erosion-affected areas.

Keywords: Erosion control; Millet; *Pennisetum*; Yield

1. Introduction

In many regions worldwide, crop yields are decreased due to wind erosion damages. Kind and extent of damages vary considerably among regions. Experiments on soils in Nigeria indicated that maize yields declined after removal of the top soil layer despite the use of chemical fertilizer (Lal, 1985). In the US Great Plains, however, a wind-erosion-affected region with low rainfall and with soils naturally low in organic matter contents, long-term crop yields have risen in general despite severe wind erosion (Dregne, 1990). On the sandy soils of the Southern Sahelian Zone (SSZ), wind erosion caused crop losses, reduced fertility and removed fine soil fractions (Wendt, 1984). Peasant farmers in Niger mentioned damages by wind erosion as one of the greatest problems for millet production (Bargel et al., 1990; Taylor-Powell et al., 1991). Sandblasting and burial of millet seedlings due to sand storms during the rainy season regularly decrease yields and can completely destroy millet crops, the main staple in the SSZ (Michels et al., 1993, 1995b). In another surveyed region in Niger, however, farmers did not consider wind erosion a major concern in the past 10 years, except in the development of microdepressions (Michels et al., 1994).

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Wind erosion control measures can consist of establishing windbreaks, soil roughening and increasing soil cover. The soil conservation function of vegetated fallows in the SSZ has given way more and more to continuous millet cultivation. Mulching with crop residue or with twigs not only reduces wind erosion and traps blown soil, but also stimulates crop growth, stabilizes and increases yields, and it is easy to apply (Bilbro and Fryrear, 1983, 1985; Bationo and Mokwunye, 1991; Unger et al., 1991; Geiger et al., 1992). Quantitative data on crop benefits from wind erosion control measures are scarce. The objective of this study was to determine effects of stover application on millet establishment and yields. In another part of this study, the effects of stover application on wind erosion and soil properties were reported (Michels et al., 1995a).

2. Materials and methods

2.1. Site and experimental layout

A field experiment was conducted during 1991 and 1992 at the ICRISAT Sahelian Center (ISC) situated in the southwestern part of Niger (13°15′N, 2°18′E, 240 m alt.). The rainy season in that area lasts from May to September and long-term average annual rainfall is 545 mm. Total annual rainfall was 603 mm during 1991 and 585 mm during 1992. Rainfall events are regularly preceded by short easternly sand storms. 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. On a field 1.5 ha in size, millet residue amounts of 500 kg ha^{-1} and 2000 kg ha^{-1} were distributed on the soil surface prior to each millet sowing and each dry season. 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 as described by Michels et al. (1995a).

2.2. Cropping system

An improved 95-d pearl millet cultivar, 'CIVT' was sown by hand in traditional "pockets" (i.e., throwing more than 10 millet seeds in a planting hole) on a 1×1 m grid on untilled soil on 27 May 1991 and 27 May 1992. Three weeks after sowing, each pocket was thinned to three plants. Nitrogen was applied as calcium ammonium nitrate at a rate of 30 kg N ha^{-1} during tillering and 15 kg N ha^{-1} during shooting. Phosphorus (20 kg P ha^{-1}) was applied as single super phosphate before sowing and incorporated slightly. The field was weeded manually 3 and 10 weeks after sowing. Insects, mainly *Dysdercus volkeri*, were controlled with 1 kg ha^{-1} Decis® (deltamethrine) 80 d after emergence (DAE) in 1991, and birds were controlled during the last 2 weeks before final harvest.

2.3. Burial of millet plants and monitoring of growth and development

After each erosion event, the number of visible plants per pocket was counted along the middle millet row of each plot (1992: two rows, spaced 6 m apart) parallel to the damaging wind direction. Plants were tagged following criteria described by Michels et al. (1993) as not covered, partially covered, and totally covered. Uncovered pockets were recorded when at least five plants per pocket emerged and none subsequently died or were covered. Partially covered pockets were recorded when five or more plants emerged but some reduction in plant number occurred later. When no plants were visible, the criterion was "totally covered". Counting was repeated until the millet was thinned at 3 weeks after emergence.

Beginning 3 to 4 weeks after emergence, plants from one not-covered and one partially covered pocket in each plot were observed weekly for phenological development until final harvest. Measurements on these plants included plant height, number of visible leaves per plant, number of nodes, and panicle length. Dry matter and leaf area (using a LI-COR 3100 leaf area meter; LI-COR, Lincoln, Nebraska) were measured biweekly in 1991 and weekly in 1992 by destructive harvest of all plants from an uncovered and a partially covered pocket in each plot. Plant samples were subdivided in stem, leaves, sheaths, and panicles. Plant components were dried in a forced draft oven at 70°C for 48 h and weighed.

2.4. Millet yields

Final harvests were made at 100 DAE in 1991 and at 114 DAE in 1992 in order to compare the effects of residues on stover and grain yields. In 1991, 72 m^2 and in 1992, 288 m^2, were harvested in each plot, respectively, and samples were subdivided into stems and panicles. Numbers of pockets without millet plants, without panicles and mature panicles were recorded. Plant components were dried at 65°C until constant weight. Panicles were threshed by hand, the grain weighed and kernel weight determined. Because of heavy damage to the panicle branches by scarabid beetle (*Rhinyptia infuscata*) and the millet head caterpillar (*Heliocheilus* (= *Raghuva*) *albipunctella*) in 1991, a "potential grain yield" was calculated by use of the rachis/grain ratio of the undamaged panicles from each sample. The rachis weight of damaged panicles was multiplied with this ratio. The total above-ground dry matter was calculated as the sum of the stover and the total weight of unthreshed panicles.

2.5. Data analysis

Analyses of variance were performed using the general linear model (GLM) procedure of the SAS software (SAS Institute, 1988) as described by Michels et al. (1995a). Growth data of "partially buried" and "not buried" plants were handled using a split-plot model with residue application as the main factor, and "burial" by soil as the subfactor. Yearly data of final grain yield and yield components were regarded as repeated measurements over time and thus analyzed using the Repeated Measures option within GLM.

3. Results

3.1. Burial of millet and induced effects on millet growth

Millet emergence (6 to 15 plants per pocket) occurred 2 d after sowing in 1991 and 3 d after sowing in 1992. There were four sand storms during the first 2 weeks after emergence in 1991, and three in 1992. Little difference among treatments was visible in the first week after emergence in 1991 despite two strong sand storms and a significant reduction in the soil flux in the 2000 kg ha^{-1} residue treatment (Table 1). Three weeks after emergence in 1991, however, more pockets were not covered with 2000 kg ha^{-1} residue than in the control or with 500 kg ha^{-1} residue. The number of totally covered millet pockets 20 DAE was lowest in the 2000 kg ha^{-1} treatments. The 500 kg ha^{-1} treatments and the control plots did not differ in any of the three burial categories 20 DAE in 1991.

In 1992, one sand storm on 1 June (2 DAE) covered more than 20% of the emerged pockets irrespective of treatments. Considerable numbers of pockets re-emerged during the following 3 d in the 500 kg ha^{-1} residue plots and the control, but not in the 2000 kg ha^{-1} residue plots. At the last observation before thinning in 1992, the 2000 kg ha^{-1} residue treatments had more not-covered and less partially covered pockets than the others, but the number of totally covered pockets was greater than in other treatments.

Table 1
Extent of millet covered by blown soil (% of pockets) as affected by crop residue application during the 1991 and 1992 rainy season, ISC, Sadoré, Niger

Burial of millet	Residues (kg ha^{-1})	Days after emergence 1991						Days after emergence 1992			
		2	3	5	10	14	20	1	3	6	17
Not											
	0	100	79	61	44	39	30	100	60	54	47
	500	100	84	60	39	37	29	100	67	56	46
	2000	100	75	65	60	57	51	100	75	58	50
Partially											
	0	0	7	20	32	29	38	0	13	27	36
	500	0	7	16	36	31	38	0	10	28	38
	2000	0	18	20	23	24	30	0	9	23	29
Totally											
	0	0	17	22	24	32	32	0	28	20	17
	500	0	12	23	26	31	33	0	22	16	16
	2000	0	13	18	17	19	19	0	21	21	21

Table 2
Dry matter (g pocket^{-1}) of not-covered and of partially covered millet, as affected by crop residue application during the 1991 and 1992 rainy season, ISC, Sadoré, Niger

	Days after emergence 1991							Days after emergence 1992							
	30	36	50	64	82	93	104	40	47	54	66	76	87	97	109
Plant burial															
Not	1.3	2.2	18.6	70	125	260	238	9.3	34	41	152	179	288	341	330
Partially	0.3	0.6	4.2	42	103	228	136	2.7	12	17	116	150	157	280	310
$LSD_{0.1}$	0.6	0.9	13.3	46	62	93	67	3.6	13	12	48	62	84	114	67
Residues (kg ha^{-1})															
0	0.4	1.8	16.2	39	131	227	216	7.9	18	13	68	107	232	209	166
500	0.7	1.1	8.1	52	81	219	176	5.3	21	29	170	147	224	398	400
2000	1.2	1.4	8.0	75	125	284	173	4.9	30	45	165	235	217	339	401
$LSD_{0.1}$	0.7	1.3	18.0	62	78	89	84	6.0	29	27	63	83	106	145	91
ANOVA	($P>F$)														
Burial	0.017	0.006	0.106	0.541	0.285	0.985	0.023	0.005	0.011	0.004	0.107	0.225	0.015	0.317	0.310
Residue	0.174	0.624	0.566	0.402	0.258	0.270	0.673	0.634	0.736	0.147	0.085	0.029	0.996	0.056	0.065
Bur. × Res.	0.419	0.365	0.636	0.235	0.816	0.168	0.527	0.246	0.491	0.689	0.474	0.502	0.621	0.134	0.419
CV (%)	134	107	199	136	79	46	57	101	95	73	58	62	63	60	33

Table 3
Millet dry matter and yield components as affected by crop residue application during the 1991 and 1992 rainy season, ISC, Sadoré, Niger

	Dry matter weight (kg ha^{-1})			1000-kernel weight (g)	Panicles per viable pocket
	Stover	Grain	Total[a]		
Year[b]					
1991	1212	379	1879	10.1	1.56
1992	1583	818	2827	10.2	3.51
Residues[b] (kg ha^{-1})					
0	1165	496	1966	10.1	2.28
500	1348	567	2252	9.9	2.29
2000	1680	732	2841	10.5	3.03
Year × Residues					
1991					
0	1095	339	1702	10.2	1.55
500	1083	308	1624	9.6	1.14
2000	1458	489	2311	10.5	1.99
$LSD_{0.1}$	338	177	579	0.7	0.42
CV(%)	26	44	29	6	25
1992					
0	1235	653	2230	9.9	3.02
500	1614	826	2880	10.2	3.43
2000	1902	974	3371	10.5	4.07
$LSD_{0.1}$	325	141	511	0.4	0.57
CV(%)	19	16	17	4	15
ANOVA[b]	$P > F$				
Year	0.069	<0.001	<0.001	0.765	<0.001
Residue	0.003	0.004	0.012	<0.001	0.006
Year × Res.	0.655	0.602	0.600	0.435	0.282

[a]Total aboveground dry matter including the chaff.
[b]Repeated-measures analyses do not yield CVs and LSDs.

Dry matter, leaf area and phenological measurements followed the same trends, therefore only dry weight will be reported. Millet plants from not-covered pockets had more biomass than those from partially covered pockets for all observation dates during both growing seasons (Table 2) but the effects were not always significant due to high coefficients of variation. There was no significant effect of residue application on the growth of unaffected and of partially affected plants in the 1991 growing season (Table 2). Only during the last weeks of the 1992 growing season did plants from residue treatments exceed the control in biomass.

3.2. Millet yields

Significant effects of the sampling year were found for all parameters except the kernel weight (Table 3). The application of residue had significant effects on all yield components. When averaged over both years, stover dry matter was increased 16% by 500 kg ha^{-1} residue and 44% by 2000 kg ha^{-1} residue compared to the control. Grain yields were increased by an average of 15% by 500 kg ha^{-1} residue and 48% by 2000 kg ha^{-1} residue. The effect of 500 kg ha^{-1} residue on grain yield was not significantly different from the control. The calculation of the potential yield for 1991 did not change the significances among treatment differences and the data are therefore not shown. The yield increase was caused primarily by a larger number of panicles per pocket and to some extent by heavier kernels. There were major differences between years in the average threshing percentage of millet panicles (0.53 in 1991; 0.65 in 1992) and the harvest index (0.19 in 1991; 0.29 in 1992), but not among treatments.

4. Discussion

4.1. Burial of millet and induced effects on millet growth

In 1991, 2000 kg ha^{-1} of residue showed the potential to protect millet seedlings against covering by moving soil, but did not provide complete protection. Michels et al. (1993) reported that sand storms destroyed an unprotected millet crop in the 1990 season; by contrast, resowing was not required in the present study. Differences in pocket burial among treatments were small in 1992 despite significantly less soil flux in the 2000 kg ha^{-1} residue treatment during the strongest storm of either year on 1 June. In an adjacent field with millet sown 1 day earlier, the storm on 1 June 1992 covered and destroyed a millet crop completely by blown soil despite 2000 kg ha^{-1} residues whereas in our trial only 20 to 30% of the crop were totally covered. This underlines the crucial importance of the crop growth stage during wind erosion events for the extent of damages to the crop. It shows furthermore the difficulties for predicting and modeling crop damages. The high residue level provided no protection to the seedlings against burial in an erosion event on 4 June 1992 (5 DAE) compared to other treatments. Thus the number of not-covered pockets were reduced between 3 DAE and 6 DAE, and the number of partially covered pockets increased for all treatments. We conclude that at least 2000 kg ha^{-1} residues are required for effective crop protection against severe wind storms.

Millet growth data from partially covered pockets in 1991 agreed with those obtained in similar measurements in 1990 (Michels et al., 1993). However, the 1992 data indicate that mechanical damage may have only small effects, if any, on millet growth in some years. In 1991, pockets of both not-covered and partially covered pockets had three plants per pocket, but in 1992 there were also partially covered pockets with two plants within the observed pockets. Thus, in 1991 the decrease in dry matter may have been caused by abrasion damage and subsequent physiological reactions, whereas in 1992 the smaller plant number probably contributed to a lower dry matter production. Damage generally depends on the amount of blown soil at a certain growth stage or on the number of subsequent storms during early development (Michels et al., 1995b). Increasing the area monitored would probably be a good measure to decrease the coefficient of variation. Experiments with artificial burial at different growth stages and with the use of portable wind tunnels in the field could provide useful information on the determinants of plant damage.

4.2. Millet yields

The 2000 kg ha^{-1} residue treatment increased both stover and grain yield in both years whereas the lower residue level was effective only in the second year. In both years, panicle number per viable pocket was greatest for the 2000 kg ha^{-1} residue level, indicating that plant nutrition effects of the residues may have contributed to the yield increases. Crop growth stimulation effects of residue were identified earlier as phosphorus mobilization due to decreased concentrations of exchangeable Al, and enhanced phytohormone production by soil microoganisms, thus enhancing root growth (Kretzschmar et al., 1991; Hafner et al., 1993). Additionally, recycling of nutrient elements following termite and microbial decomposition have been reported (Geiger et al., 1992).

One disadvantage of using millet stover as mulching material is potential infestation of the following millet crop with *Coniesta* (=*Acigona*) *ignefusalis* (ICRISAT Sahelian Center, 1991). Another is that residues can increase the amounts of weeds within millet fields (Bationo et al., 1993) and thus affect nutrient and soil-water balances. After soil wetting, evaporation is initially less from residue-covered than from bare soil due to reduced surface wind speeds and temperatures. The further drying, however, is prolonged for a covered soil. It remains wetter near the surface resulting in a similar or even greater cumulative evaporation than bare soil (Unger et al., 1991). In the semiarid Great Plains region, the available soil water was increased by use of 10 t ha^{-1} or more of millet mulch (Bilbro and Fryrear, 1991), but in Niger 25 t ha^{-1} had no effects on profile water storage during the dry season (Payne et al., 1990).

Despite fertilizer applications, stover yields of 2000 kg ha^{-1} and more which appear necessary for an effective soil flux reduction were not obtained in either treatment. In on-farm experiments in Niger, millet stover yields without fertilizer application ranged from 470 to 2400 kg ha^{-1} (McIntire and Fussell, 1989). In other surveys, stover yields of 1750 kg ha^{-1} were found in central Niger (350–425 mm), and 2940 kg ha^{-1} in the wet zone (600 mm) (ICRISAT Sahelian Center, 1992). Due to animal grazing, however, the amount remaining up to the onset of the following season is often only 100 to 200 kg ha^{-1}. Powell and Fussell (1993) pointed out the crucial importance of reducing the competition between livestock and soil fertility. Minimal amounts of stover were harvested for alternative uses or were digested by termites (ICRISAT Sahelian Center, 1992). Around urban centers, however, farmers profit from a rising market value for the crop residues (Speirs and Olsen, 1992), which increases the opportunity costs for wind erosion control. An increase in biomass production through the use of fertilizers is urgently needed.

Village-level surveys indicated that farmers were aware of wind erosion, and that they reacted by applying millet stalks and other mulching materials such as branches from trees on parts of the field surface (Raulin, 1965; Bargel et al., 1990; Taylor-Powell et al., 1991). Due to material shortages, they only cover eroded and degraded spots, in order to trap windblown soil, instead of entire fields, which they considered as an appropriate measure for conservation of soil productivity (Lamers and Feil, 1993). Lack of residue materials appears to be the major constraint for a broadcast soil cover. Even small amounts can be effective in restoring vegetation, however, as indicated by an experiment on a bare forest soil. A 15–20% soil cover of branches and twigs in combination with tillage operations resulted in the production of 900 kg ha^{-1} biomass after 1 year whereas the untreated control remained barren (Chase and Boudouresque, 1987).

5. Conclusions

The application of 500 kg ha^{-1} residue had no effect on millet establishment and resulted in small increases in dry matter production. An amount of 2000 kg ha^{-1} decreased the extent of millet seedlings buried by blown soil except during severe wind storms. Grain yield and stover production were increased by both protection against wind erosion and direct growth stimulation. Amounts of 2000 kg ha^{-1} residue cannot be expected on fields of peasant farmers in the region without higher levels of external inputs. Farmers strategies to cover only unfertile plots with mulch material appear rational. Increased biomass production by the use of fertilizers is needed for soil conservation and crop protection in wind-erosion-affected areas. For final recommendations, an economic evaluation of alternative stover uses and different wind erosion control measures is needed.

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