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Wind erosion in the Southern Sahelian Zone and induced constraints to pearl millet production

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Abstract

On the sandy soils in the Southern Sahelian Zone, wind erosion owing to frequent short sand storms, especially at the beginning of the rainy season, is one of the constraints to crop growth. Sand storms and their effects on millet burial and growth were monitored during the 1990 growing season at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Center, Niamey, Niger. During the growing season, the accumulated sand captured at 0.1 m above the soil surface attained 1262 kg m^{-2} vertical sampler opening. Ninety per cent of the millet pockets sown with the first rains were covered at 22 days after emergence and the crop was resown. During one single wind erosion event, 384 kg m^{-2} of sand was trapped and 40% of all millet pockets were totally covered. Surviving plants from the partially covered pockets showed delays in growth and development. The maximum plant height and leaf number were lower with a significant reduction in the leaf area index. Grain yield from unaffected pockets was nearly twice that of the pockets which were partially covered. Protection measures against wind erosion may have a potential to stabilize millet production in the Southern Sahelian Zone.

1. Introduction

The climate in the West African Sudano-Sahelian Zone is governed by two different wind regimes. During the dry season, from November to March, a dry northeastern wind (the ‘Harmattan’) blows from the Sahara desert. No rainfed crops are grown in that period, but significant nutrient inputs into the soils occur with the deposits of the Harmattan dusts (Drees et al., 1992). During the rainy season, from May/June to September/October, the prevailing winds blow from the southwest, disturbed by strong eastern monsoon wind and rain storms. Storms of about 15–60 min duration, including gusts with maximum wind speeds up to 100 km h^{-1}, regularly preceed these rainfall

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events, mainly during the first half of the rainy season when soils are bare (Sivakumar, 1989). They result in transporting sand near to the ground that buries young seedlings and in producing impressive red dust clouds that reduce visibility sometimes to less than 30 m.

Arenosols or deep sandy soils occupy 29.9 million ha or 22.5% of the total area in the Sudano-Sahelian zone (Sivakumar, 1989). The textural composition of these soils is primarily sand; over 85% to a depth of 2 m or more. Large parts of the arable area in the Southern Sahelian zone are cropped with pearl millet (*Pennisetum glaucum* (L.) R. Br.), usually in association with cowpea (*Vigna unguiculata* (L.) Walp.). In the traditional cropping systems in Niger, millet is sown with the first rains in May or June. Crop establishment is often poor because of extended dry periods after sowing or to sand burial owing to wind erosion, which makes replantings necessary (Mclntire and Fussell, 1989). The major constraints for millet yields are poor soil fertility, lack of rainfall, high soil surface temperatures and damage by wind-blown sand.

Several coinciding factors favor the occurence of wind erosion. Intensification of land use in marginal areas, overgrazing of pastures, and the removal of trees and shrubs as well as the occurence of droughts, led to a degradation of the soil cover (Mainguet and Chemin, 1977; Sivakumar et al., 1992). The low contents of both organic matter (< 0.2%) and fine soil particles prohibit the building of nonerosive aggregates on the sandy soils. Soil crusts are sometimes formed through a cycle of rain and soil drying (Hoogmoed and Stroosnijder, 1984). The loose sand lying on such crusts is easily blown away. Texture and climatic conditions favor rapid surface drying which makes it easier for erosive forces to translocate soil material. Large planting distances for millet between 1 and 2 m, and slow crop establishment increase the damaging effects of wind. Unfavorable conditions force farmers to replant the millet crop several times owing to combined water and erosion stress.

The objectives of this study were to quantify the amounts of wind-blown sand within a millet field that is left bare at the time of sowing and to measure the influence of wind-blown sand on stand establishment and the growth of millet. A nondestructive method to quantify crop damage by sand burial in the field was developed.

2. Materials and methods

2.1. *Experimental site and lavout*

The field experiment was conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Center (ISC) located at Sadore (13°06′N, 2°21′E), 45 km south of Niamey, Niger, during the 1990 rainy season. The soil is classified as a (sandy, siliceous, isohyperthermic) Psammentic Paleustalf of the Labucheri soil series, according to the US Soil Taxonomy (West et al., 1984). Mean annual rainfall at ISC is 562 mm; however, in 1990 total rainfall was only 399 mm and the onset of rains occured on 23 May. The size of the experimental field was 90 m × 170 m. To facilitate quantification of wind erosion effects, the field was divided in 153 quadrats each measuring 10 m × 10 m (Fig. 1). The field was cleaned of all millet residues from the previous year before sowing.

2.2. *Wind erosion*

To quantify the amount of moving sand during the growing season, a sampling mast with one field sand trap at 0.1, 0.35, 0.5, 0.75, 1.0, 1.5, 2.0 and 2.75 m height above the soil surface was installed at the center of the field. The sand traps were of the BSNE (Big Spring Number Eight) type with a collection efficiency of 88–94%, as developed by Fryrear (1986a). Wind-blown soil particles passed through a vertical slot 20 mm wide and 50 mm

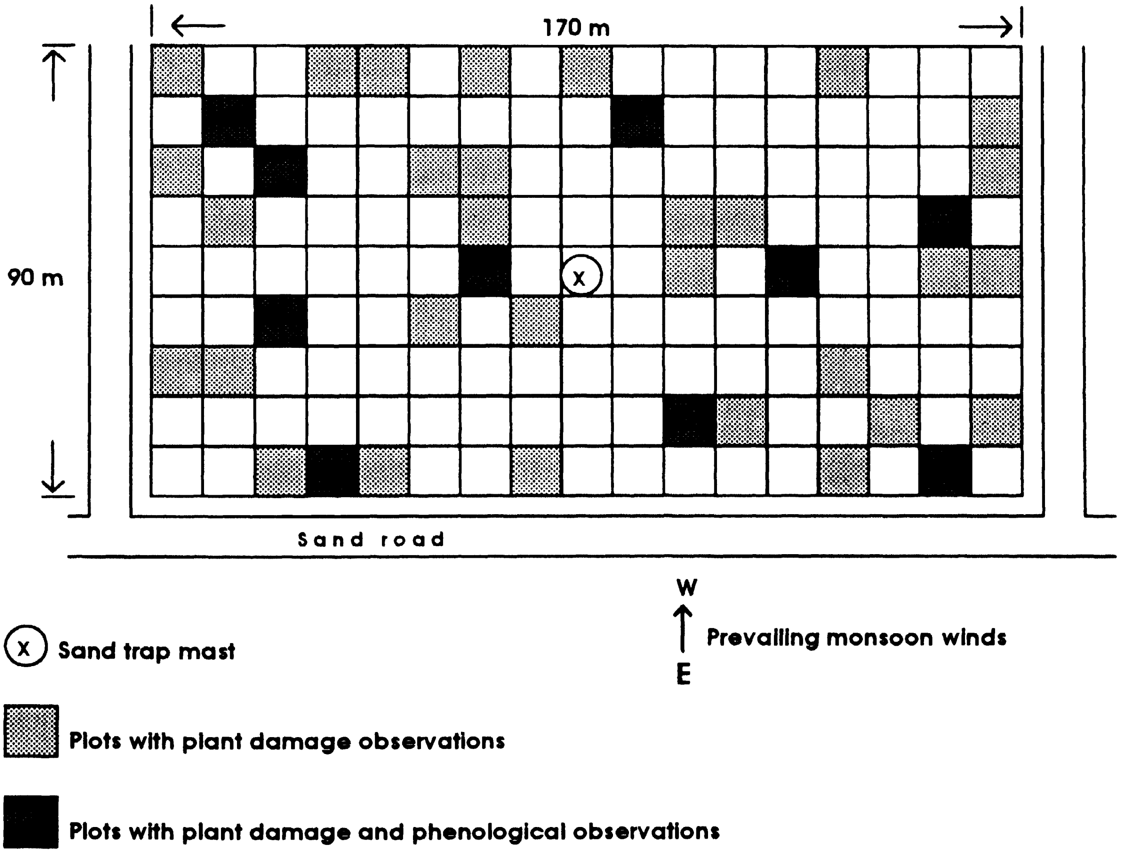

Fig. 1. Field plan of the 153 quadrants.

high at each of the sampling heights and were captured. The distance of the sampling mast to the eastern field border, a well-packed sand road, was 40 m. The area outside the eastern border consisted of some bushes and few trees within traditional millet fields. After each erosion event, the soil caught in each sampler was washed onto a No. 44 Whatman filter paper (Whatman International, Maidstone, UK), dried at 110°C for 48 h and weighed. The equipment was installed shortly after the millet sowing, thus storms before 25 May were not sampled.

The vertical distribution of wind-blown soil was calculated with the combined suspension/saltation equation as proposed by Vories and Fryrear (1991):

$$W_i(y) = \frac{C_i}{392y^{1.35}} + c_i \exp(d_i y) \tag{1}$$

where w_i is the amount of soil (in kg m^{-2} vertical sampler opening) captured during the erosion event i at the height y (in m) and the terms $c_i/392y^{1.35}$ and c_i $\exp(d_i y)$ describe the amount of soil moving in suspension and in saltation mode, respectively. The expression $c_i/392$ is a suspension coefficient and 1.35 corresponds to the suspension exponent; c_i is a saltation coefficient and d_i is a saltation exponent. Parameters c and d were calculated for each storm by a nonlinear regression analysis, using the sampler height as a weighting factor, with the Statistical Analysis Systems Institute (SAS) software procedure NLIN (SAS, 1988). In order to obtain the moving soil mass per meter width for each storm, the vertical distribution curve was integrated between the 0.1 and 2.0 m heights, the range typically sampled.

2.3. *Planting system*

Millet cultivar CIVT was sown on 24 May in planting pockets spaced 1 m × 1 m and on the flat. The method of sowing was similar to the farmers practice in the region. A hole (0.05–0.15 m deep) was opened up in the soil with a long hand hoe, 20–100 seeds are thrown into the hole, which was then covered with soil and compressed by the foot. The millet crop experienced several sand storms afterwards and 90% of the emerged pockets were completly covered by 18 June. Hence, millet was resown after a 17 mm rain on 25 June. After the second sowing, the field was weeded manually three times during the season (after 3, 5 and 9 weeks). Three weeks after sowing, pockets were thinned to three plants each, as is the recommended practice. Final harvest was done 99 days after emergence on 5 October.

2.4. *Burial of millet*

A nondestructive method was developed in order to monitor the effects of sand storms on millet establishment. Of the 153 quadrats, 40 quadrats were selected randomly (Fig. 1). After millet emergence, the number of visible plants per pocket was counted between and after erosion events in the 40 quadrats. The observed pockets were subdivided in three categories following the criterion of number of visible plants per pocket: more than four plants ('not covered'); one to four plants ('partially covered'); no plant visible ('totally covered'). After resowing on 25 June, emergence was less than 100%; all data presented here are expressed as a percentage of initially emerged pockets, not of pockets sown. Counting was repeated until the millet was thinned on 17 July, 3 weeks after the second sowing date.

2.5. *Millet growth and development*

One plant from one uncovered pocket and one partially covered pocket in ten of the 40 randomly chosen quadrats was tagged. Beginning 3 weeks after emergence, tagged plants were observed weekly for phenological development until final harvest. Measurements on the tagged plants included plant height, the number of visible leaves per plant, number of nodes and panicle length. Dry matter and leaf area (using a LICOR 3100 leaf area meter; LI-COR, Lincoln, NE, USA) were measured weekly in these ten quadrats by destructive harvest of all plants, both from an uncovered and a partially covered pocket. Plant samples were subdivided into stem, leaves and panicles. Plant components were oven dried at 70°C for 48 h and weighed.

3. Results

3.1. *Wind erosion*

The erosion period during 1990 lasted about 3 months with a total of 21 erosive events following the installation of the equipment. Visual observations indicated that most of the soil movement stopped a few minutes after the onset of rainfall. Amounts of sand captured at all heights, storm events and calculated storm parameters are shown in Table 1. The amount of trapped sand decreased exponentially with the height above the soil surface. The differing values for the curve parameters, c and d, indicate changing soil mass amounts and distributions for each erosion event. The total amount of moving sand during the growing season reached 1261.5 kg m^{-2} for the 0.1 m height which corresponded to an overall integrated mass flux of 124.5 kg m^{-1} width between 0.1 and 2.0 m above the ground.

3.2. *Burial of millet*

During the first week after sowing in May, three erosion events took place

Table 1
Storm related wind erosion data during the 1990 rainy season, ISC, Niger

Date	DAE[a]	Measured soil flux (kg m^{-2}) at eight sampler heights (m)								Calculated erosion parameters[b]			
		0.10	0.35	0.50	0.75	1.00	1.50	2.00	2.75	c	d	R^2	Q (kg m^{-1})
27 May	1	4.08	0.15	0.10	0.18	0.09	0.08	0.09	0.06	24.98	−22.650	0.982	0.38
29 May	3	63.18	7.18	1.76	0.72	0.50	0.28	0.37	0.12	139.68	−9.264	0.999	7.45
31 May	5	13.18	2.40	1.02	0.12	0.08	0.04	0.03	0.01	23.31	−6.769	0.999	2.00
9 June	14	12.37	1.67	0.64	0.53	0.59	0.65	0.62	0.33	24.68	−8.044	0.897	1.63
13 June	18	21.48	1.27	0.48	0.22	0.30	0.25	0.19	0.35	103.09	−18.888	0.994	1.92
16 June	21	11.17	2.27	1.82	3.66	1.85	1.75	1.72	1.99	24.69	−8.044	0.414	1.63
18 June	23	23.36	3.65	1.81	1.92	1.73	1.80	1.72	1.76	41.03	−6.712	0.735	3.56
22 June	27	47.47	2.82	0.52	0.16	0.08	0.09	0.11	0.04	143.68	−12.988	0.998	4.54
25 June	30	122.05	7.59	2.30	1.70	1.26	0.81	0.61	0.55	400.53	−13.969	0.999	11.34
3 July	6	15.12	1.80	0.57	0.26	0.00	0.00	0.00	0.00	32.10	−8.826	0.999	1.85
6 July	9	383.63	28.63	13.32	6.94	5.58	3.79	2.97	1.42	2396.29	−22.731	0.999	36.25
9 July	12	12.03	0.99	0.43	0.26	0.23	0.12	0.10	0.01	30.88	−10.974	0.996	1.27
14 July	17	9.72	0.43	0.16	0.20	0.21	0.18	0.03	0.04	44.36	−18.220	0.996	0.86
16 July	19	32.06	2.62	0.80	0.08	0.12	0.08	0.07	0.06	81.87	−10.968	0.999	3.36
25 July	28	35.10	0.80	0.40	0.20	0.11	0.00	0.00	0.00	123.96	−15.011	0.994	3.15
27 July	30	68.60	3.40	0.90	0.20	0.10	0.10	0.20	0.00	219.89	−13.735	0.998	6.38
4 Aug.	38	139.20	5.80	2.50	0.00	0.00	0.00	0.00	0.00	487.68	−14.773	0.998	12.70
9 Aug.	43	87.80	3.30	1.00	0.50	0.00	0.00	0.00	0.00	296.45	−14.365	0.996	8.05
14 Aug.	48	23.40	2.00	0.90	0.00	0.00	0.00	0.00	0.00	56.63	−10.359	0.998	2.54
18 Aug.	52	95.30	2.10	0.71	0.10	0.00	0.00	0.00	0.00	329.33	−14.714	0.992	8.63
20 Aug.	54	41.20	2.00	0.00	1.10	0.90	0.40	0.10	0.20	130.87	−13.620	0.997	3.85
Seasonal total:		1261.50	82.87	32.14	19.05	13.73	10.42	8.93	6.94				123.34

[a] DAE, days after (millet) emergence.

[b] c and d are regression parameters for Equation 1, R^2 equals the weighted sum of squares owing to regression divided by the weighted sum of squares of the uncorrected total. Q is the soil mass passing a 1 mm wide slot with a vertical height from 0.1 to 2.0 m.

and the accumulated amount of moving sand reached more than 80 kg m^{-2} at the 0.1 m measurement height. As a result, 60% of all millet pockets were totally covered after a few days while about 20% were partially covered by sand (Fig. 2(A)). Further erosion events took place for 25 days after sowing. On 18 June when only 3% of the monitored pockets were marked 'uncovered' and the number of totally covered pockets was 90%, we regarded the crop as being completely damaged.

The first rain after the second sowing was preceded by a sand movement of 383.6 kg m^{-2} at the 0.1 m measurement height. This single event constituted about 30% of the sand trapped during the entire season at that height and 40% of the emerged millet pockets were totally buried (Fig. 2(B)). Two weeks after sowing, the height of surviving plants was not more than 3 cm, although there was no further sand movement in the second week. In the following week, millet emerged again in some of the totally covered pockets. The effect of further erosion events on the millet pockets was less considerable, although the total sand amount during crop growth reached 943 kg m^{-2} at the 0.1 m height.

3.3. *Crop growth and development*

Most crop damage could be attributed to the burial of seedlings by moving sand, but leaf tip and edge damage by sand abrasion were rarely visible. However, surviving millet plants from the partially covered and uncovered pockets showed consistent differences in their growth and phenological development during the entire growing season. Maximum leaf area index

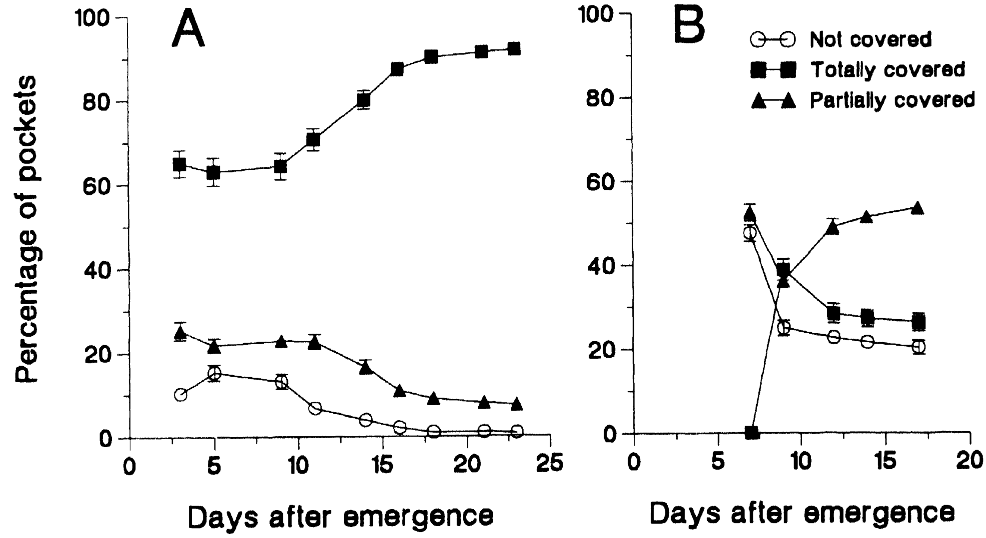

Fig. 2. Extent of millet covered by blown soil. A: millet sown on 24 May. B: millet sown on 25 June. ISC, Sadore, Niger, 1990. I, standard error of the mean. In some cases, the standard error is smaller than the curve symbol.

(LAI) was reached 63 days after emergence and was much higher in the not covered pockets compared with the partially covered pockets (Fig. 3(A)). At 28 days after emergence, leaf number from the partially covered pockets was 35% lower than in the unaffected pockets. Differences were smaller later in the season (Fig. 3(B)).

A maximum plant height of 1.6 m was reached 10 weeks after sowing in the not covered pockets. The maximum height of plants from partially covered pockets was 75% of the maximum height of plants from not covered pockets and it occured 2 weeks later. Panicle emergence began in the ninth week after emergence in the not covered and 2 weeks later in the partially covered pockets. Maximum panicle length was reached after 13 weeks, with an average length reduction of nearly 50% when compared with unaffected plants. Tiller and node number per plant as affected by sand coverage showed similar differences and are therefore not shown.

The above-ground biomass production of uncovered plants reached a

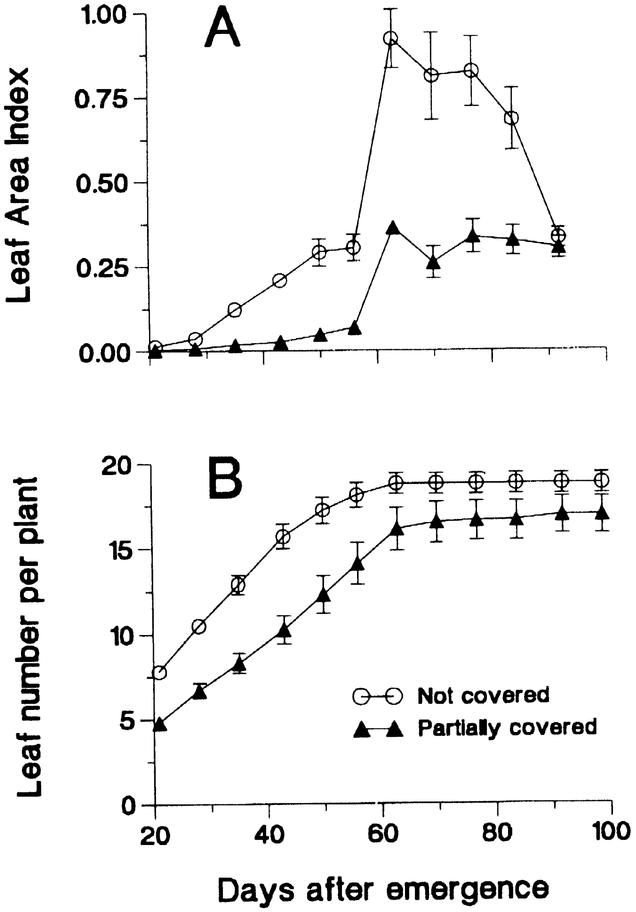

Fig. 3. Leaf area index (A) and leaf number (B) as affected by sand coverage. ISC, Sadore, Niger, 1990. I, standard error of the mean. In some cases, the standard error is smaller than the curve symbol.

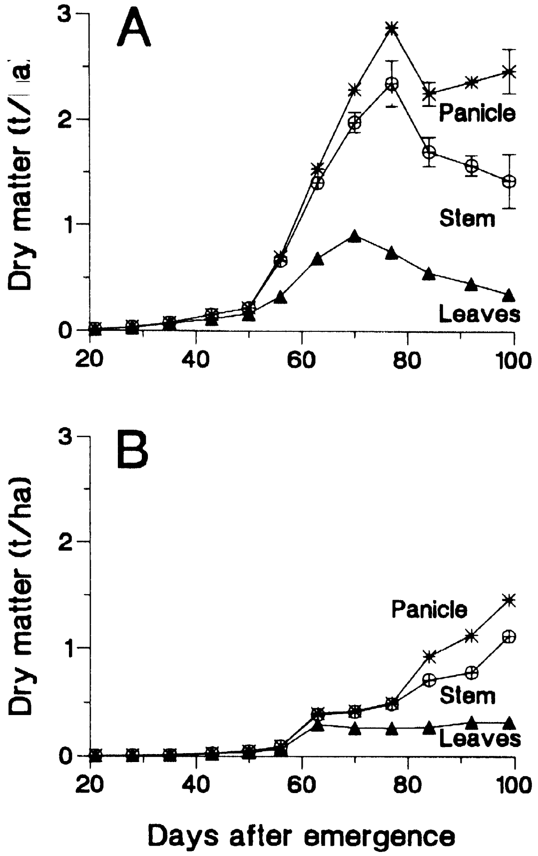

Fig. 4. Millet dry matter production as affected by sand coverage. A: uncovered pockets. B: pockets partially covered. ISC, Sadore, Niger, 1990. I: standard error of the mean. In some cases, the standard error is smaller than the curve symbol.

maximum of 2.87 t ha^{-1} (Fig. 4(A)); plants from partially covered pockets attained 1.46 t ha^{-1} dry matter (Fig. 4(B)). Millet grain yield of 0.57 t ha^{-1} from not covered plants was nearly twice the yield of covered ones, 0.3 t ha^{-1}, which was due to an increased average grain number per panicle.

4. Discussion

The measured extent of wind eroded soil (Table 1) is less than that in published data from other regions. On a bare field in Big Spring, Texas, a total mass of 4267 kg m^{-2} at the 0.15 m measurement height was recorded during a 100 days period using BSNE samplers (Zobeck and Fryrear, 1986). Storms in that semi-arid region lasted more than 10 h, much longer than the storms observed at ISC. Saltation coefficients (c) between 1000 and 5340 were recorded in half of the 1988 erosion events at Big Spring (Vories and Fryrear, 1991).

However, even the soil movements in this reported research resulted in considerable long-term effects on degradation or rebuilding of the top soil. Ten meter wide strips of the perennial grass *Andropogon gayanus* Kunth at ISC were estimated to catch sand amounts of 2000 t ha^{-1} within 3 years (Renard and Vandenbeldt, 1990). Topographic measurements showed an increased soil surface elevation of 0.15 m after 5 years of mulching with millet residues at ISC (Geiger et al., 1992). The authors attributed this change to the entrapment of wind-blown material, as well as to the protection against erosive forces. A soil chemical analysis of blown soil from ISC showed that the investigated sample had a pH, cation exchange capacity and base status similar to what the authors called a 'productive soil' (Scott-Wendt et al., 1988). The authors refer to wind erosion as one of the primary genetic sources of soil variability.

Damage to millet depends not only on soil surface conditions and wind characteristics, but also very strongly on the crop growth stage. One single storm at 3 days after crop emergence buried more than 60% of the pockets. However, the much higher amount of blown sand on 5 July (6 days after emergence) had less impact, even though the emerging crop had suffered a dry period after the resowing on 25 June. The duration of the sensitive period for sand burial can be shortened through measures for improved vigor. Bationo et al. (1992) reported that the application of N and P fertilizer promoted early growth and increased the final plant density by 49%. The traditional way of millet sowing appears to have major impacts on the extent of crop damage. The compression of the soil in each pocket facilated the accumulation of moving sand and thus the partial or complete burial of the young millet plants. However, the seedling cluster probably increased the ability to recover after being buried; but surface crusts developed when the upper soil layer dried and prohibited or delayed re-emergence. With soil temperatures sometimes more than 50°C in the upper 0.05 m during May and June, the surviving seedlings quite possibly suffered a combination of mechanical and heat stress, sometimes in addition to water shortage, as reported for millet at ISC in 1990 (VanDenBeldt and Williams, 1992). The traditional seedling cluster appears to be an instrument to prevent covering and it probably also increases the ability to recover after being buried.

In this study, we observed growth reduction and development delays of plants affected by wind erosion. As the length of the rainy season for many locations in Niger has decreased since 1965 (Sivakumar, 1992), delayed crops may not reach physiological maturity at all. Fryrear (1986b) mentioned growth delays of between 10 and 28 days caused by erosion effects, mainly by abrasion damage. On the other hand, delayed plants may survive during drought spells, when advanced plants suffer more from water stress owing to higher physiological demands. The physiological responses of the delayed growth of partially buried plants remains unclear. Armbrust (1982) reported reduced photosynthesis and increased respiration for sorghum plants after sandblast damage in the wind tunnel. In our situation, however, the combination of heat, mechanical and probably water stress after burying added a complex dimension.

The survey method to categorize the pocket burying can be quite easily applied to large sample sizes. However, owing to physical and chemical soil microvariability, and the harsh climatic conditions, the observed reductions in plant number per pocket cannot be attributed entirely to the burial by blown sand. Also, the recovery of buried plants depends on the extent of the damage, as well as on other stress factors. Another disadvantage of the method used is the disregarding of the relative status of a single plant. A plant which is not affected at all, is considered the same in our monitoring as a plant whose leaf tips are barely visible. A future improvement could be the combination with recent developed radiometer technology (Nageswara et al., 1992) to also assess visible leaf area with a nondestructive method.

Control measures against wind erosion problems are well-documented. Soil roughening, windbreaks and surface cover have been shown to reduce the susceptibility of both soils and crops to wind erosion forces (Skidmore and Hagen, 1977; Bilbro and Fryrear, 1985; Fryrear, 1987, 1989). These measures have been tested at ISC for suitability. It should be recognized, as emphasized by Salem (1991), that solutions to erosion problems in arid regions may not be found only in palliative measures like mechanical conservation structures, but in the evolution of integrated land management systems.

5. Final remarks

Wind erosion in millet fields in the Southern Sahelian Zone has negative impacts on millet growth, and probably on short- and long-term soil fertility, as well as on soil microvariability. In areas susceptible to wind erosion, farmers must replant several times and in years with a short rainy season, growth delays of plants affected by wind erosion may prohibit grain production all together. Future research should be directed towards a regional survey and a characterization of the areas most affected by wind erosion. It appears useful to estimate the soil loss of field areas using additional surface creep samplers, as well as to investigate the economic effects of both crop damage and soil loss.

Efforts need to be directed towards the characterization of the storms and determination of soil surface parameters such as erodibility, and of the parameters c and d as influenced by a growing crop. Models, such as the Wind Erosion Prediction System (Hagen, 1991), can be used to identify further research needs in order to understand the physical processes and to simulate the influence of control measures. However, difficulties to adapt such models should not be underestimated, as the recent Sahelian agricultural systems differ widely from industrialized crop production. A valuable long-term project would be a region-wide wind erosion probability map for the important crops in the region.

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