Wind Erosion Research in Niger: The Experience of ICRISAT and Advanced Research Organizations

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Abstract

In the Sahelian zone of Niger, wind erosion constitutes one of the major causes of land degradation. This results from low vegetation cover at a time when the most erosive winds are blowing in combination with sandy, easily erodible soils. Through their effect on soil cover, overgrazing by cattle and the rapid expansion of agricultural land have further enhanced the impact of wind erosion on the Sahelian agro-ecosystem. Wind-erosion-induced damage includes direct damage to crops through sandblasting, seedling burial following sand deposition, and topsoil loss. Although seedling burial can substantially impact crop yield in individual years, the loss of topsoil is by far the more worrying consequence of wind erosion because of its potentially long-term effect on the soil resource base. Available data indicate that several tens of tonnes of topsoil and tens of kilograms of plant-essential nutrients per hectare can be lost to the wind in just a few storms under favorable conditions. However, simple and effective wind-erosion control techniques have been developed to reduce or even arrest wind-induced land degradation. The extent of wind erosion in Niger, as well as the efficiency of various control techniques such as ridging, surface mulch, and wind breaks, are discussed here.

Introduction

Wind erosion is one of the main factors contributing to land degradation in the semi-arid tropics. It has been estimated that in the arid and semi-arid zones of the world, 24% of cultivated land and 41% of pasture land are affected by moderate to severe land degradation from wind erosion (Rozanov 1990). Within these climatic zones, the Sahel is considered to suffer from particularly acute wind erosion problems (UNEP 1992).

In the Sahelian zone of West Africa, the rapid population growth of recent decades has lead to a rapid increase in cultivated area, the expansion of agriculture into more marginal areas, and an increased pressure on land as a result of grazing and deforestation. Consequently, the area of soil left bare, ~~and~~ therefore directly exposed to wind, has increased considerably. In the case of Niger in particular, the effect of these changes in land use on wind erosion is aggravated by the very nature of the soil, which is frequently poorly aggregated and sandy, offering little resistance to wind erosive forces.

Wind-erosion-induced damage includes direct damage to crops through sandblasting, burial of seedlings under sand deposits, and loss of topsoil (see, e.g., Fryrear 1971; Ambrust 1984; Fryrear 1990). The first two types of damage have an immediate effect on crop yield. However, the loss of topsoil is particularly worrying, since it potentially affects the soil resource base and hence crop productivity on a long-term basis, by removing the layer of soil that is inherently rich in nutrients and organic matter. Analysis based on the nature of sand formations in the Sahara and its Sahelian fringe indicates that most of the Sahel is presently a zone of net deposition of wind-transported material (Mainguet 1990). However, because of the diffuse nature of the phenomenon, accurate mass balances on a regional scale are difficult to estimate. Furthermore, as the degradation process proceeds, these balances may be reversed. Mainguet (1990) and Mainguet and Chemin (1991) observed local changes in sand formations and in the particle size distribution of the sand fraction, indicating a shift from net deposition to net soil loss by wind erosion.

Although regional estimates of wind erosion provide valuable information for the global assessment of degradation and the evaluation of off-site impact, such large-scale approaches do not provide information on wind-mediated transfers of soil on the field scale. These transfers of soil within fields or between fields and surrounding land over distances ranging from a few meters to a few kilometers have important repercussions for crop production and for the subsistence farmers living off the land (Sterk et al. 1996). Indeed, these processes may not only result in more rapidly declining yields, but also enhance field-scale variability through the redistribution of soil material (Scott-Wendt et al. 1988), or promote other land degradation processes such as water erosion by increasing the aerial extent of surface crusts.

The importance of wind erosion in the process of land degradation in the Sahelian zone of West Africa was recognized early by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). Starting in 1985, a long series of studies on wind erosion and control measures was initiated, frequently in collaboration with other advanced research organizations, at the ICRISAT Sahelian Center (ISC) in Sadoré, Niger. This paper provides an overview of past collaborative research at ISC, and ongoing research projects in wind erosion by scientists from ICRISAT and other international institutes.

Physical Environment

Rainfall

The climate in the Sahelian zone of Niger is to a large extent regulated by the seasonal fluctuations of the Intertropical Convergence Zone (ITCZ). The

ITCZ travels north and south in response to the apparent movement of the sun. Rainfall generally follows the passage of the ITCZ, with most rainfall falling in a 75–90 day period from June to September. Rainfall ranges from 300 mm in the northern Sahelian zone to 600 mm at its southern limit. Rainfall is highly variable in time and space (Sivakumar et al. 1993) and often comes in the form of convective storms. In Niamey, the average monthly maximum (daytime) temperature ranges from 33 °C in January to 41 °C in April. PET at Niamey amounts to 2,294 mm per year and exceeds rainfall in all months except August (Sivakumar et al. 1993).

Rainfall is frequently preceded by strong winds lasting from a few minutes to an hour, with maximum wind speeds seldom exceeding 15 m/s (Table 1; Michels et al. 1995b). A prolonged dry season lasts from October to May. Periods of dry easterly harmattan winds loaded with fine dust dominate from October to March. Harmattan wind speeds are lower than for the convective storms, usually less than 7 m/s (Michels et al. 1995b). From April to the start of the rainy season, one observes a mixture of easterly harmattan winds and southwesterly monsoon-type winds. Total sand flux during the dry season, measured at 0.1 m above the soil surface, constitutes less than 15% of the total annual sand flux (Michels et al. 1995b).

Table 1. Duration and maximum wind speed registered for wind storms during the 1992 rainy season (Michels et al. 1995a).

Date	DAE	Wind storms		
		Duration (min)	Duration >6 m/s (min)	Maximum speed (m/s)
6 May		na	na	na
12 May		35	9	7.0
24 May		56	7	9.5
25 May		4	3	6.7
28 May		19	16	13.6
1 June	2	69	57	19.6
4 June	5	64	37	11.3
13 June	14	42	11	7.8
14 June	15	12	7	7.2
20 June	21	41	37	8.9
24 June	25	na	0	5.8
2 July	33	28	25	10.3
18 July	49	75	47	8.1
27 July	58	18	18	9.7
31 July	62	154	34	13.3

Soil and Vegetation

A wide diversity of soils is found in Niger. However, arenosols—deep sandy soils—occupy by themselves 43% of the land used for agro-sylvo-pastoral activities in the Sahel of Niger (100–600 mm; FAO 1973). These soils typically contain >85% sand, have a particulate structure, especially in the surface horizon, and low organic matter content. Water-holding capacity is low, and the infiltration rate is high in the absence of surface crust. As a result, the soil surface dries out rapidly, rendering it sensitive again to wind erosion very soon after rainfall. At ISC, soils belong to the order of arenosols. They have developed from aeolian sandy deposits. In the A-horizon, they typically contain 3% clay and 90% sand, of which 95% is between 0.05 and 0.5 mm (West et al. 1984). Organic C is generally less than 0.3%. The rainfall and temperature of the Sahel lead to the development of an open savanna of grasses and low bushes, scattered with individual trees. At the end of the dry season, the vegetation cover is often very low, as a result of the prolonged dry season and grazing by cattle.

Farming Systems

In Niger, as in most of the Sahel, decision making by farmers concerning the management of their agricultural land is largely governed by the need to ensure short-term food sufficiency at the household level. Agriculture has therefore remained extensive in nature, with low levels of external inputs. Fertility maintenance relies heavily on the practice of fallowing, with additional inputs of nutrients from cattle feces.

Millet or millet-based intercropping occupies 90% of the agricultural land. Yield in Niger over the 1989–1991 period averaged 340 kg grain/ha and approximately 1,200 kg straw/ha (Baidu-Forson and Williams 1996). Land preparation is minimal, other than the clearing of vegetation and sometimes the burning of crop residue. At the start of the rainy season, residue levels seldom exceed 500 kg/ha as a result of grazing, decomposition by termites, or their use as construction or fencing material (Lamers and Buentrup 1996). However, farmers sometimes consciously concentrate crop residues in order to reclaim low productivity areas in their fields. The trapping of wind-blown sediment by residue is thought to contribute to the reclamation process (Chase and Boudouresque 1987; Lamers and Feil 1995; Léonard and Rajot, 1997).

Millet is generally sown with the first good rain. The low planting density (3,000–5,000 hills/ha) and low levels of surface residue mean that the soil is left with little or no protection against wind erosion for several months before planting and for at least 6–8 weeks after the start of the rainy season. Manual weeding is practiced 1–3 times per season, which further reduces surface roughness and accelerates surface drying. The traditional sowing practice, which consists of throwing 20–40 seeds into a shallow hole dug with a hand-held hoe before closing it with the foot, leaves behind small depressions which favor sand accumulation and burial of the seedlings.

Research Highlights

Soil and Nutrient Loss and Deposition

Research on the extent of soil and nutrient transfers through wind-blown sediment in Niger has focused on two main areas: 1) the quantification of vertical particle flux, mainly dust deposition, and 2) the measurement of horizontal soil flux across fields by the combined processes of saltation and suspension.

Dust transport

Dust refers to particles <60 mm in equivalent diameter. This fine fraction is often rich in mineral elements. Because of their small size, dust particles are transported by suspension in the air and are susceptible to being carried by wind over considerable distances. The quantification of dust uplifting, transport, and deposition in areas prone to dust storms is therefore important in view of the potentially significant contribution of this sized fraction to the nutrient balance of the agro-ecosystems.

Two studies on dust deposition have been reported in Niger since 1985 (Drees et al. 1993; Herrmann et al. 1996). An additional study was initiated in 1995 by ORSTOM in Banizoumbou, Niger, 60 km east of Niamey. All three studies made use of passive dust catchers to quantify dust deposition rates. The catchers comprise boxes (that open horizontally) placed a few meters above the ground. The measured total annual deposition of dust particles in the region of Niamey ranges from 740 to 1,640 kg/ha/yr (Table 2). There was a tendency towards a decrease in the annual deposition rate over the 1985–1996 period.

Table 2. Annual deposition rate of dust in the region of Niamey, Niger, and percentage deposited between mid-April and mid-July (early Monsoon period).

Year	Annual deposition (kg/ha) per year	Early monsoon (% of annual)
1985–1986[†]	1,640	50
1992[‡]	1,250	58
1993[‡]	820	50
1994[‡]	760	59
1996[§]	740	49

[†] ISC (Drees et al. 1993).
[‡] ISC (Herrmann 1996).
[§] Banizoumbou, unpublished.

Between 21 and 40% of the annual dust deposition occurs between mid-October and mid-April. The main deposition events during this period result from the passage of dust clouds carried by harmattan winds, which often last for several days. Forty nine to fifty nine percent of the annual dust deposition occurs between mid-April and mid-July, as a result of monsoon winds and the passage of convective storms (Table 2). As opposed to the harmattan dust storms, these deposition events last for less than one day. Herrmann et al. (1996) found that, on average, over 11 storms, 60% of dust deposition during the rainy season, occurs as rainout, i.e., as a result of dust trapping by raindrops.

On the basis of the mineralogical composition of dust samples, Herrmann et al. (1996) conclude that airborne dust during the harmattan events originates in Tchad, south of the Tibesti mountains. Furthermore, he observes that the <63 mm fraction (potential dust fraction) of the top 3 cm of the soil has a similar mineralogy and silt/clay ratio to the harmattan dust, and is markedly different from the fine fraction of the B-horizon. This similarity between the potential dust fraction of the soil and the harmattan dust provides evidence for the occurrence of net deposition of dust during the harmattan season (Herrmann et al. 1996). Total elemental chemical analysis shows that the nutrient content of the potential dust fraction of the top 3 cm of the soil is comparable to the dust fraction collected after the passage of convective storms (Table 3). It is, however, poorer in nutrients than the dust deposited during harmattan dust storms, probably as a result of weathering and leaching during the rainy season. These findings suggest that most of the dust caught during the rainy season is remobilized locally during the convective storms.

Table 3. Element content of dust and clay + silt fraction (<63 µm) of soil at Sadoré, Niger (Herrmann et al. 11996).

		Na (%)	K (%)	Ca (%)	Mg (%)	P (mg/kg)
Harmattan dust	Jan. 1992	0.46	1.58	1.91	0.77	638
Convective storm dust	June 1992	0.13	1.03	0.38	0.3	389
Surface soil	0–3 cm[†]	0.11	1.15	0.25	0.32	660
Subsoil	38–60 cm[†]	0.15	0.55	0.05	0.12	377

[†] Sampling depth.

Herrmann (1996) demonstrates the existence of a strong north–south gradient in dust deposition rates, from 1,560 kg/ha per year at Ouallam (14° 19' N) to 620 kg/ha per year at Tara (11° 55' N), i.e. a southward gradient of approximately -3 kg/ha per year per kilometer. The author attributes the decrease in dust load to the gradual deposition of dust particles by gravitational settling as the distance from the dust source increases. This process is mostly applicable during the harmattan season, when the dust travels over large distances. In addition, during the rainy season, the intensity of deposition is closely linked to the number and severity of convective storms, both of which decrease southward.

On the basis of the total elemental chemical analysis of dust and rainwater, it was estimated that an average of 12.7, 16.3, 5.3, and 0.7 kg/ha of K, Ca, Mg, and P, respectively, could be deposited annually as a result of dust deposition at Sadoré, Niger (13° 15' N). Most of this is deposited as solids, except for Ca, for which 58% of the deposition occurs in dissolved form. By comparison, a millet crop of 2,000 kg/ha straw and 600 kg/ha grain requires approximately 60 kg K/ha and 5 kg P/ha (Buerkert 1995). Hence, if all dust trapped in the passive dust catchers were effectively deposited at the soil surface without further re-entrainment, the input of nutrients through dust would amount to about 20% of the mineral requirement for the production of a good millet crop.

Little data exists on the extent of re-entrainment of fine particles by wind. Rajot et al. (1996) measured vertical fluxes of dust particles from a bare field during a single monsoon wind event prior to the start of the rainy season. They estimated losses at 2 kg dust/ha. In the absence of subsequent rain, this fine sediment can potentially be transported over long distances. Furthermore, since no rain occurred prior to the measurement, one may assume that a large fraction of this entrained sediment corresponds to recently deposited dust. Although the calculated value would indicate rather low rates of re-entrainment, further measurements are required for a better evaluation of this term.

The studies of Herrmann et al. (1994) point to the existence of close interactions between the processes of dust deposition and crust formation. Indeed, the authors observe higher silt contents in the top 3 cm than in the immediately underlying layers. On these sandy soils, crust formation is very sensitive to small changes in silt + clay content. Hence, dust deposition may enhance crust formation on these coarse-textured soils. At the same time, crust formation leads, in its initial stage, to a segregation of particles in the top few millimeters of the soil, leaving the sand particles at the surface (Bielders and Baveye 1996). This particle segregation process induced by drop impact can in turn favor the subsequent entrainment of sand particles by wind.

Soil transport

In this section, we discuss the transport of soil irrespective of particle size, by the combined processes of creep, saltation, and suspension. However, because of the texture of the soil considered here, the bulk of the mass transport relates to particles >60 mm. In all cases the data presented refers to horizontal fluxes of sediment.

Earlier studies on wind erosion were restricted to measurement of the intensity of horizontal flux of airborne sediment as affected by specific surface conditions (see, e.g., Banzhaf et al. 1992; Buerkert et al. 1995; Michels et al. 1995b). Since the experimental setup did not allow for any mass balance calculations to be made, such data cannot be used to calculate actual soil losses by wind erosion. More quantitative data has been obtained from measurements of changes in surface elevation of plots exposed to wind action. After a four year period, Renard and Vandenbeldt (1990) found a difference in elevation of 150 mm between adjacent bare millet plots and plots planted with the perennial grass *Andropogon gayanus*. Similarly, Geiger et al. (1992) observed height differences of 150 mm between bare millet plots and plots that received 2 t/ha of millet stover over five years. For both these studies, one cannot distinguish between the respective contribution of erosion and deposition to the measured changes in elevation, since only relative height difference was measured. Michels et al. (1995b) and Buerkert et al. (1996) carried out repeated measurements of surface topography over time on the same plots. Michels et al. (1995b) reports an average decrease in surface elevation of 33 mm in bare millet plots after 1 year. The data need to be interpreted with caution, however, as the number of elevation measurement points was very low. Between mid-September and the end of July 1994, Buerkert et al. (1996) measured a change in elevation on bare millet plots of 12 mm, equivalent to a soil loss of about 190 t/ha. The measured soil losses are, however, the result of the combined action of wind and water erosion, the control plots having developed extensive erosion crusts over time.

Probably the most accurate estimates of soil loss by wind erosion for Sahelian conditions have been reported by Sterk and Stein (1997), following intensive monitoring of soil mass flux at 21 locations in a 40 × 60 m experimental plot covered with a 0.8 t/ha millet stover mulch. Using geostatistical procedures, they derived precise estimates of incoming and outgoing horizontal mass transport rates. Mass balance calculations revealed a total soil loss of 45.9 t/ha during four convective storms (Table 4). Soil losses of similar magnitude were measured in an on-farm experiment at Banizoumbou, Niger. Based on measured soil fluxes between 0 and 35 cm above ground on bare plots, we have estimated from mass balance calculations that at least 55 t soil/ha were lost during the 1995 rainy season (Fig. 1) and 24 t soil/ha during the 1996 season. Using the ^{132}Cs technique, Chappell et al. (1996) estimated soil erosion losses on sandy plains close to Banizoumbou at 50.3 t/ha per year over the last 30 years. Although wind erosion may have contributed significantly to the total soil loss, one cannot estimate its contribution precisely, since the ^{132}Cs technique does not discriminate between losses by wind or water erosion.

Table 4. Calculated soil and nutrient losses during four storms in 1993 (Sterk et al. 1996).

Date	Soil loss (t/ha)	N loss (kg/ha)	P loss (kg/ha)	K loss (kg/ha)
13 June	12.5	4.9	0.9	11.2
27 June	2.0	na	na	na
30 June	4.6	na	na	na
1 July	26.8	13.4	5.2	45.9
Total	45.9	18.3	6.1	57.1

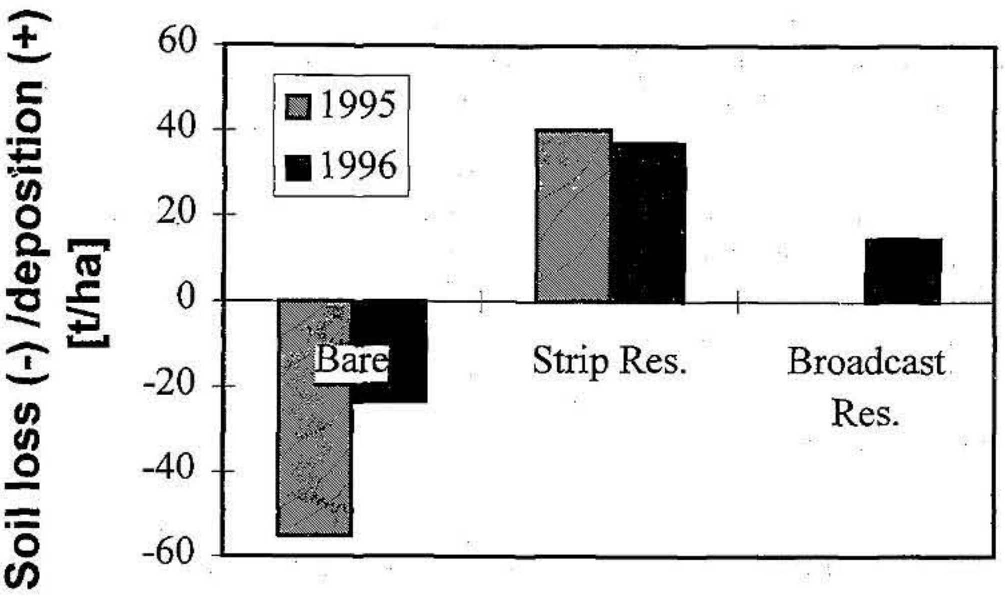

Figure 1. Total soil loss or deposition during the 1995 and 1996 rainy seasons at Banizoumbou, Niger, on bare plots and plots with 2 t/ha of millet stover mulch applied either in strips or broadcast (1996 only). Stover was applied at the start of the season.

The above data provide strong evidence of extensive losses of soil for bare fields directly exposed to the erosive action of wind. However, the reported rates of soil erosion by wind may represent extremes, since they were measured on bare plots devoid of any crop residue. In practice, in farmer fields, residue levels at the start of the rainy season are generally of the order of 0.3 to 0.5 t/ha. However, such low levels of crop residue may have very little impact on the intensity of soil erosion by wind, especially at high wind velocities (Michels et al. 1995b; Sterk 1997).

For the sandy soils considered here, one can assume that most of the mass transport by wind occurs through creep and saltation. Such processes are effective only over relatively short distances. Changes in surface roughness such as a transition from cultivated to fallow land, or variations in the surface mulch, could have a large effect on mass transport and even shift the mass balance from erosion to deposition. Reports on the occurrence of soil deposition are mainly limited to cases with high levels of crop residue mulch. For instance, Léonard and Rajot (1996) observed sand accumulation of up to 50 mm over two years in small degraded plots covered with 10 t/ha of grass straw and small branches. Recent measurements on fallow land at Banizoumbou, Niger confirm the very low horizontal soil flux compared to millet fields (Bielders, unpublished data). These observations emphasize that, on a mass basis, wind erosion on sandy soils consists in a local redistribution of soil material on the field scale. Despite the short-range transport, this process cannot be considered negligible because of the strong impact such soil loss may have on field-scale crop productivity. Once degraded, it may be virtually impossible, within the means accessible to farmers, to reclaim degraded land. Furthermore, as opposed to soil, nutrient transport is not restricted to local redistribution, since a large fraction of the total nutrients is present in the fine sediment, which can travel in suspension over large distances.

Sterk et al. (1996) provide the only estimates of nutrient loss by wind erosion for Niger. For the experiment described above, they calculated nutrient flux based on the nutrient content of the trapped sediment for the two largest storms. The results show a total loss of 57.1 and 6.1 kg/ha of K and P, respectively (Table 4). These amounts are roughly equivalent to the quantity of K and P required to produce a millet yield of 2,000 kg straw and 600 kg of grain/ha. They also correspond to approximately 3% of the nutrients contained in the top 10 cm of the soil. Over the same period, Sterk et al. (1997) measured nutrient inputs of 2.5 and 0.2 kg/ha of K and P, respectively, from dust deposition. This study emphasizes the potentially dramatic negative impact of wind erosion on soil productivity.

Crop Damage

Direct damage to crops during sand storms can result in the loss of plant tissue and reduced photosynthetic activity as a result of sandblasting, or in the burial of seedlings by deposited sand. These aspects were studied for millet under field conditions at ISC and in wind tunnel experiments at the USDA Wind Erosion Laboratory in Manhattan, Kansas.

Michels et al. (1995a) report on the effect of wind speeds ranging from 8 to 14 m/s, and sand fluxes ranging from 0 to 42 g/m per second on millet growth and photosynthetic activity in a wind tunnel experiment. Plants were exposed for 15 minutes at 8 days after emergence (DAE), 16 DAE, or on both dates. The authors observed that millet survival was 100% in all cases, indicating a much higher tolerance of millet against sandblasting damage than for other crops (Fryrear 1971; Fryrear and Downes 1975). However, sandblasted plants saw their viable leaf area reduced by an average of 19% across all treatments at 21 DAE, compared to the control. New leaves were observed to grow rapidly after exposure, and at 57 DAE no significant difference could be found between twice-exposed plants and the controls. In addition to the loss of viable leaf area, sandblasting affected photosynthesis in the viable parts of the leaves (Michels et al. 1995a). The photosynthetic activity of viable leaves for plants exposed 8 DAE was reduced by an average of 55% one hour after exposure, and was still reduced by 28% four days later. Exposure to sandblasting also reduced millet dry weight at the early stages of development. At 57 DAE, the dry weight of plants exposed once was not significantly different from the control. Plants exposed twice had 5% less dry matter than once-exposed plants.

No final harvest data are available for the above experiment. However, the data indicate that, under optimal recovery conditions, millet has a good ability to recover from losses in viable leaf area and reduced photosynthetic activity induced by sandblasting. Brenner (1991) similarly reports reduced leaf area and dry matter production of young millet plants as a result of sandblasting during violent storms. However, at 46 days after sowing the crop had entirely recovered from these stresses.

As a result of the traditional sowing technique, which leaves behind small depressions, burial of seedlings under deposited wind-blown sand frequently occurs during convective storms, sometimes necessitating partial or total resowing of the crop. In a 1990 field experiment sown in the traditional way, 90% of millet hills were covered by sand 23 DAE, which necessitated re-sowing and therefore increased the risk of exposure of the crop to an end-of-season drought (Fig. 2; Michels et al. 1993). Hence, the most extensive damage to crops in that experiment resulted from burial. However, for those hills that were not entirely covered by sand, the number of leaves per plant and LAI were significantly higher throughout the season for unburied plants than for plants that had been partially covered. Final grain yield was reduced by half for partially covered hills, from 0.57 to 0.3 t/ha (Fig. 3), which was largely attributable to a lower average number of grains per panicle.

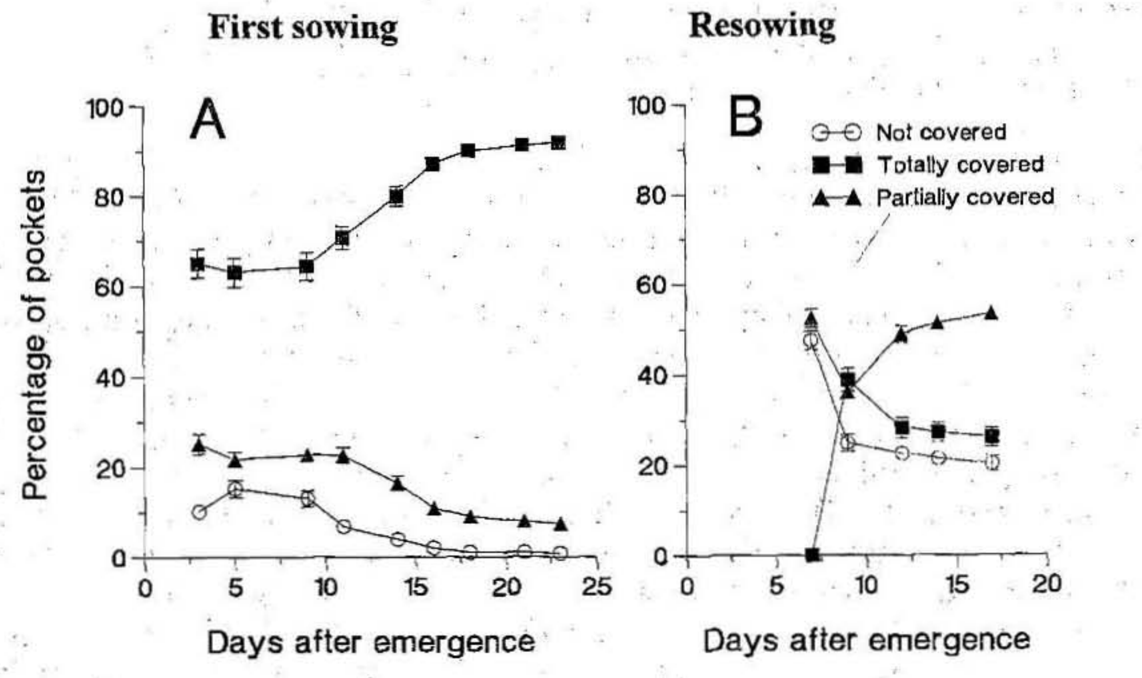

Figure 2. Coverage of millet pockets with soil during the 1990 rainy season at ISC (Michels 1994).

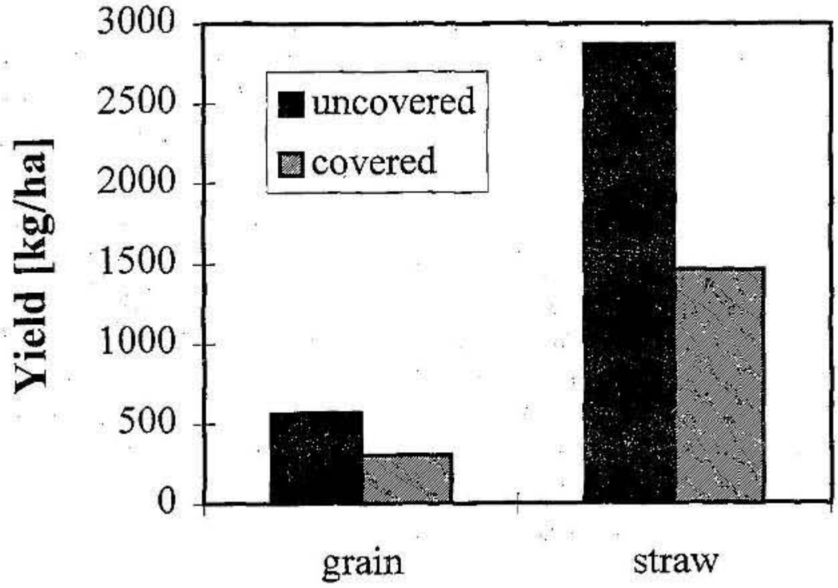

Figure 3. Effect of partial seedling burial by sand on millet grain and straw yields (Michels 1994).

It is commonly argued that planting in tufts, as practiced by Nigerian farmers, improves emergence by reducing sandblasting damage to seedlings. For instance, Klaij and Hoogmoed (1989) observed that seedling survival under field conditions was better with hill planting of 20–30 seeds per hill than with direct drilling. Michels et al. (1995a) investigated the effect of the seeding system (3 or 15 seeds per pot) and burial under 15 mm of sand on potted plants exposed to a wind tunnel sandstorm at 2, 5, and 8 DAE. Non-buried plants showed 100% survival, corresponding to the presence of at least three plants per pot. For buried plants, the highest survival rate was observed for millet planted in tufts. Similarly, dry matter at 70 DAE was nearly five times larger for buried plants sown in tufts than for single plants. However, dry matter production for unburied millet planted in tufts was 5% lower than for single-planted seed at 70 DAE, perhaps as a result of increased competition for nutrients at the higher sowing density. These results show that the advantage of planting in tufts seems to lie in the better recovery of buried plants rather than reduced injury. Michels et al. (1995a) also found that survival was higher for plants buried 2 DAE than at later dates, which they attribute to the higher seed reserves available to younger seedlings for growth through the added sand layer. Dry matter production followed the same trend.

In addition to direct effects of partial burial on yield-determining factors, such as number of tillers and panicle length, partially-buried plants show delayed development compared to unburied plants. Michels et al. (1993) found that panicle development was delayed approximately two weeks after partial burial.

The results of Michels et al. (1995a) indicate that millet shows a remarkable ability to recover from wind-erosion-induced damage under optimal recovery conditions. Since damage to millet strongly depends on plant age, the risk posed by sandblasting and burial will, to a large extend, depend on the strength and timing of sand storms with respect to the time of sowing. Furthermore, the evidence indicates that decisive damage may occur when several sources of stress are combined, as may frequently be the case under field conditions. For instance, although it had no effect on unburied plants, exposure of seedlings to sandblasting prior to burial reduced dry matter production at 70 DAE by 47% compared to unexposed buried plants (Fig. 4; Michels et al. 1995a). The delayed development resulting from burial of seedlings may further increase the risk of an end-of-season drought stress to millet by extending the crop cycle beyond the usual growing season. More generally, burial of seedlings may accentuate the effect of high surface temperatures by bringing the meristems of young seedlings directly into contact with the hot soil surface. Nutrient and water deficiencies at this critical stage may further hamper seedling recovery.

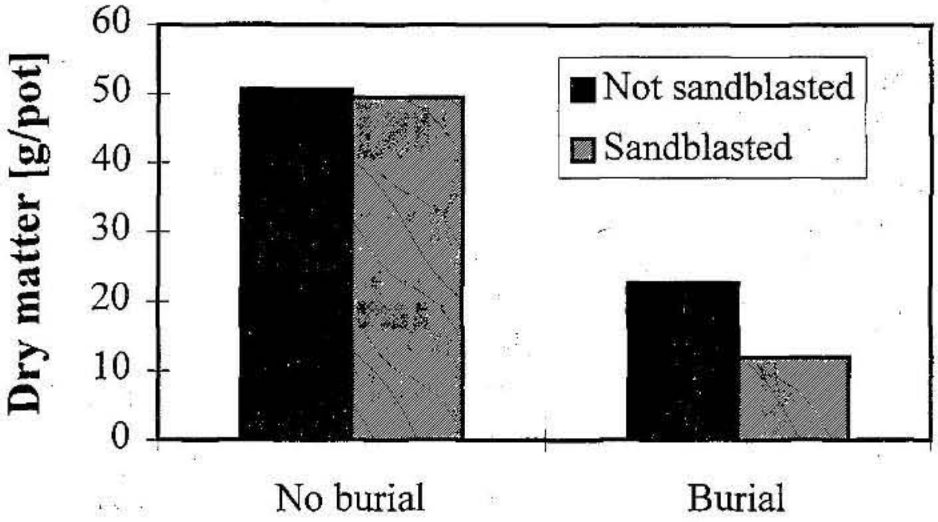

Figure 4. Effect of sandblasting and burial on millet dry matter at 70 DAE (Michels 1994).

Wind-erosion Control Measures

Wind-erosion control measures can generally be fitted within one of three categories: mechanical tillage operations, residue management, and vegetative barriers. These methods aim at decreasing wind speed at the soil surface by increasing surface roughness and/or increasing the threshold friction velocity needed to initiate particle movement by wind. Besides their use for soil conservation, erosion control methods can also reduce direct damage to crops, as discussed in the previous section. Extensive research has been carried out at ISC on all three types of wind-erosion control measures.

Crop residue management

From a technical point of view, crop residue management is probably one of the simplest alternatives for wind-erosion control in a resource-poor environment such as the Sahel. Although farmers occasionally use branches from bushes or trees, or other sources of organic mulches for the reclamation of degraded spots (Lamers and Feil 1995), the most widespread source of mulch is millet stover. Because of its value as feed for cattle as well as for other household purposes, the quantities of millet stover available at the start of the rainy season are generally low and this limits the widespread use of crop residue for mulching.

Nevertheless, the potential of crop residue mulches as a cheap and effective means of controlling wind erosion is widely recognized, even among farmer communities. Research has therefore been carried out at ISC on the use of millet stover mulches for improving plant stand establishment and reducing soil loss under Sahelian conditions, to define optimal quantities and appropriate crop residue management practices.

The effectiveness of various levels of crop residue for reducing soil loss has been studied by Michels et al. (1995b), Buerkert et al. (1995) and Sterk (1997). Over a two year period, Michels et al. (1995b) observed that the application of 2 t/ha of millet stover reduced soil flux at a 0.1 m height by an average of 47% during the rainy season (Fig. 5). No significant reduction in soil flux could be measured with a 0.5 t/ha application. In a different experiment, involving seven windbreak species, Michels (1994) reported an average reduction is soil mass flux of 56% over three years following the application of 2 t/ha of crop residue, irrespective of the windbreak species.

Buerkert et al. (1995) measured an average decrease in mass transport of 42% over two years in the presence of a 2 t/ha millet stover mulch, a reduction similar to that found by Michels et al. (1995b). Whereas bare plots lost 190 t/ha (12 mm) of topsoil between mid-September 1993 and the end of July 1994, topographical measurements on the mulched plots indicated a net soil deposition of 270 t/ha (17 mm) over the same time period (Buerkert et al. 1995). Of this 270 t/ha, 107 t/ha was deposited during the late dry season, probably mainly due to Monsoon-type winds. In accordance with the data of Buerkert et al. (1995), Geiger et al. (1992) found that relative height differences of 150 mm developed over five years between the surface of bare plots and mulched plots. In this latter case, however, one cannot distinguish between the respective contributions of losses on bare plots and deposition on mulched plots.

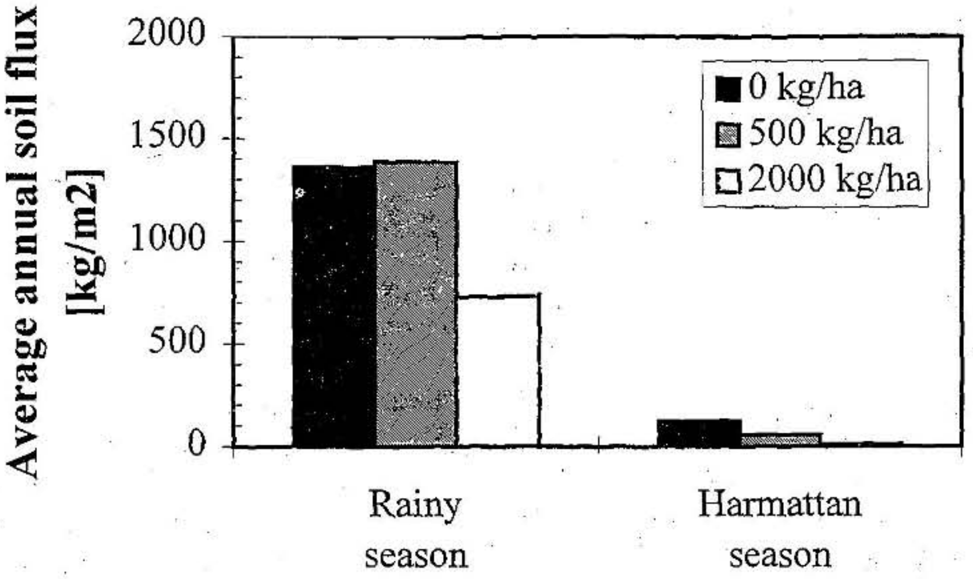

Figure 5. Average annual soil flux (1991/92) at a height of 0.1 m as affected by mulching rate during the rainy season and the dry harmattan season (Michels 1994).

Following upon the work of Michels et al. (1995b), Sterk (1997) tested two intermediate mulch application rates, namely 1 and 1.5 t/ha. This author observed a tendency for the effectiveness of crop residue mulches to decrease with increasing wind velocity. For wind velocities increasing from 8.3 to 10.6 m/s, mass flux reduction efficiency dropped from 80 to 50% at the mulching rate of 1.5 t/ha. Michels et al. (1995b) observed similarly that the efficiency of millet stover for reducing soil flux was higher during the dry season than during the rainy season (53% and 92% for the 0.5 and 2 t/ha application rate respectively), which was attributed primarily to the lower average wind speeds that characterize the harmattan winds (Fig. 5). These authors also observed that the effectiveness of crop residue seemed to increase as the severity of the sand storm decreased. The overall higher flux reduction efficiencies found by Sterk (1997), compared to Michels et al. (1995b), are likely to be the result of a different experimental set-up as well as to differences in the type of sand trap used and in the procedure for calculating the flux reduction.

At a wind velocity exceeding 11 m/s the presence of 1 t/ha millet stover actually enhanced wind erosion (Sterk, 1997), although this observation was limited to a single storm. This was ascribed to the increased turbulence near the soil surface due to the roughness created by the millet stems. Whether the same effect also occurs for the 1.5 t/ha rate and at what wind speed could not be assessed from the data.

In an ongoing experiment at Banizoumbou, 60 km northeast of Niamey in a farmer's field, we tested the effect of application mode of a 2 t/ha millet stover mulch on soil loss by wind erosion (unpublished data). In 1995, it was estimated, from the difference in input and output sand flux between 0 and 35 cm height, that bare plots lost an average of 55 t/ha, whereas deposition occurred in plots with residue placed in 30 cm wide strips amounting to 40 t/ha (Fig. 1). Actual soil loss/deposition is likely to have been higher because the mass balance calculations were restricted to events with approximately easterly winds as a result of the experimental layout. Although the convective storms frequently originate from the east, erosive events with different wind directions are also observed during the rainy season. Net soil loss on bare plots and deposition on residue plots was consistent over the entire season. In 1996, an estimated 37 t soil/ha was deposited on the mulched plots, compared to a net erosion of 24 t/ha on bare plots. In this second year, strip residue was compared with broadcast residue at the same application rate. Calculations indicate that the broadcast application trapped approximately 60% less soil than banded residue. It is believed that this effect is largely related to the greater "dead volume" within the strips, which is capable of trapping and protecting from further erosion large quantities of sand. For residue broadcast at a rate of 2 t/ha, which corresponds to a surface coverage of approximately 7% (Michels et al. 1995b), such trapping occurs mainly in the immediate vicinity of the millet stems.

As a result of the degradation that took place following wind erosion on bare plots at Banizoumbou, millet yield dropped from 328 kg grain/ha in the first year to 78 kg/ha in the second year (Fig. 6). Millet grain yield in the residue plots remained stable at about 500 kg/ha, indicating relatively comparable environmental conditions in the two years of the experiment. Although nutrient depletion may contribute to degradation, it is likely that rapid decline in soil productivity results from large losses of topsoil by wind erosion.

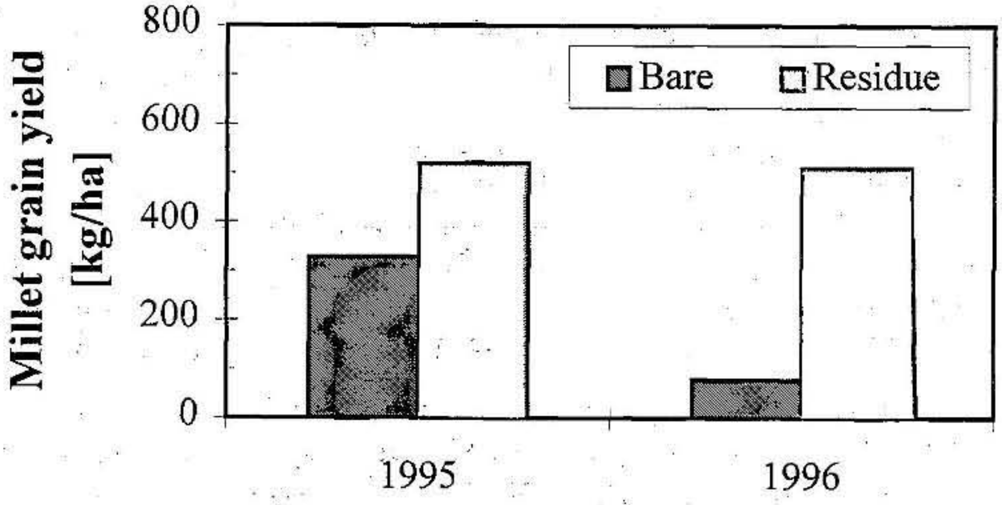

Figure 6. Effect of strip application of millet stover on millet yield at Banizoumbou, Niger.

The application of 2 t/ha of crop residue significantly modifies the surface properties of the soil. Michels et al. (1995b) found an increase in fine sand and clay and a decrease in the coarse sand fraction in the top 1 cm. The absence of mulch seems to have favored the disappearance of the 63–200 µm fraction, a fraction that is highly sensitive to transport by wind. Changes in soil chemical properties were found only in plots with the 2 t/ha application rate, with significant increases in pH, organic C, and ECEC. The respective contributions of wind erosion/deposition and decomposition of crop residue in these observed changes could not, however, be evaluated.

Buerkert et al. (1995) attempted to separate the physical "soil conserving" functions of crop residue from the chemical and the physical effects due to residue decomposition and the stimulation of soil fauna during a three year experiment. They compared a millet stover mulch at a rate of 2 t/ha with a synthetic mulch of comparable physical properties. The synthetic mulch was equally effective at reducing wind blown sand flux, yet soil deposition was more than doubled on the millet stover plots compared to the synthetic mulch. This may have been caused by the gradual decay of the synthetic mulch, which was not renewed during the course of the experiment, and by a difference in the effectiveness in the control of water erosion rather than wind erosion. These two degradation processes were largely confounded in this experiment. In the first year the synthetic mulch did not increase millet yield over the bare control, whereas it did improve millet grain and dry matter in the second year. This probably reflects the faster degradation taking place on the bare plots. The positive effect of the synthetic mulch cannot be attributed solely to soil conservation, however, since it was shown that the mulch also significantly reduced soil mechanical resistance.

The effect of millet stover mulching on millet stand establishment was studied by Michels et al. (1995c), who observed that, in agreement with soil flux data, the number of hills not covered by sand in the first weeks following sowing was highest for the 2 t/ha application rate. No significant difference in terms of seedling burial could be found between the 0.5 t/ha rate and the bare controls over the two years of the study. Final yield increased with the application rate of crop residue, which is likely to be the result of the combined effects of the physical, chemical, and biological changes in soil properties induced by crop residues. However, based on the earlier-discussed finding that total dry matter of millet from uncovered hills was higher than for partially covered hills, it may be concluded that the yield increase at the higher application rate could be partly due to the physical protection of seedlings against burial by sand.

Based on the soil flux and seedling burial data presented above, it is clear that an application rate of 0.5 t/ha of millet stover provides insufficient protection against wind erosion. Because of the overall higher efficiency in soil mass flux reduction of the 1.5 t/ha application compared to 1 t/ha, Sterk (1997) recommends the use of the higher application rate for wind-erosion control. This rate is somewhat more accessible to farmers than the 2 t/ha rate tested by

Michels et al. (1995c). It is not known whether this rate would also provide suitable protection of seedlings against burial. The data of Michels et al. (1995c) indicate that even at a rate of 2 t/ha, the protection against burial is only partial. However, whether at a rate of 1.5 or 2 t/ha, it is evident that the widespread use of mulching will require substantial increases in dry matter yield, which can only be achieved through improved management practices, including the use of inorganic fertilizers.

Mechanical measures

As opposed to crop residue, the use of tillage operations to control wind erosion damage is, in principle, not constrained by the present levels of productivity in the Sahel. However, because of the need for animal traction, the weakness of animals at the end of the dry season, and the detrimental effects of delayed sowing on millet yield, tillage is not widely practiced on the sandy soils of the Sahelian zone. Tillage nevertheless constitutes a potential alternative for wind-erosion control where residue management is constrained by availability.

The beneficial effects of plowing and ridging on millet-stand establishment have been well documented. In a three year experiment Klaij and Hoogmoed (1993) showed that early plant establishment was highest for plowed soil, followed by ridging and no-till plots (Fig. 7). The effect of tillage on establishment was strongest in the two years when sowing was followed by strongly erosive events. However, particularly in the case of ridging, the positive early effect of tillage was lost later during the season. In two years out of three the final stands at 80–90 days after sowing were essentially identical for ridged and no-till plots. On the contrary, plowed plots consistently maintained a higher population density than the other treatments. In the first year (1984), no grain was harvested because of a severe end-of-season drought. Over the last two years of the experiment, ridging and plowing improved millet yield on unfertilized plots by 30 and 83%, respectively, over the no-till plots. Similar trends were reported by Klaij and Hoogmoed (1993) for another experiment.

On the weakly-structured sandy soils typical of the region, the effect of plowing on surface roughness is rather short-lived. The beneficial effect of plowing on plant stand establishment is therefore likely to have been caused by improved root growth due to soil loosening rather than any protection against wind erosion. The same probably applies, to some extent, to the ridged treatments, although the rugosity created by ridges will last for at least a few weeks, depending on climatic conditions, and therefore will be more effective at reducing wind velocity. In addition to the lower sand flux occurring over ridged plots, it is likely that planting on top of the ridge also prevents seedling burial from occurring, although no firm data exist on this aspect. In a 12 year experiment at a site that is sheltered against the effect of wind, ridging and plowing consistently improved millet grain and straw yields (Klaij, unpublished data), but the yield advantage of ridging in this case was on the order of 10%

only. It is possible that the yield advantage of ridging is higher on plots exposed to the erosive action of wind than on protected plots, although insufficient data is available to support this assertion.

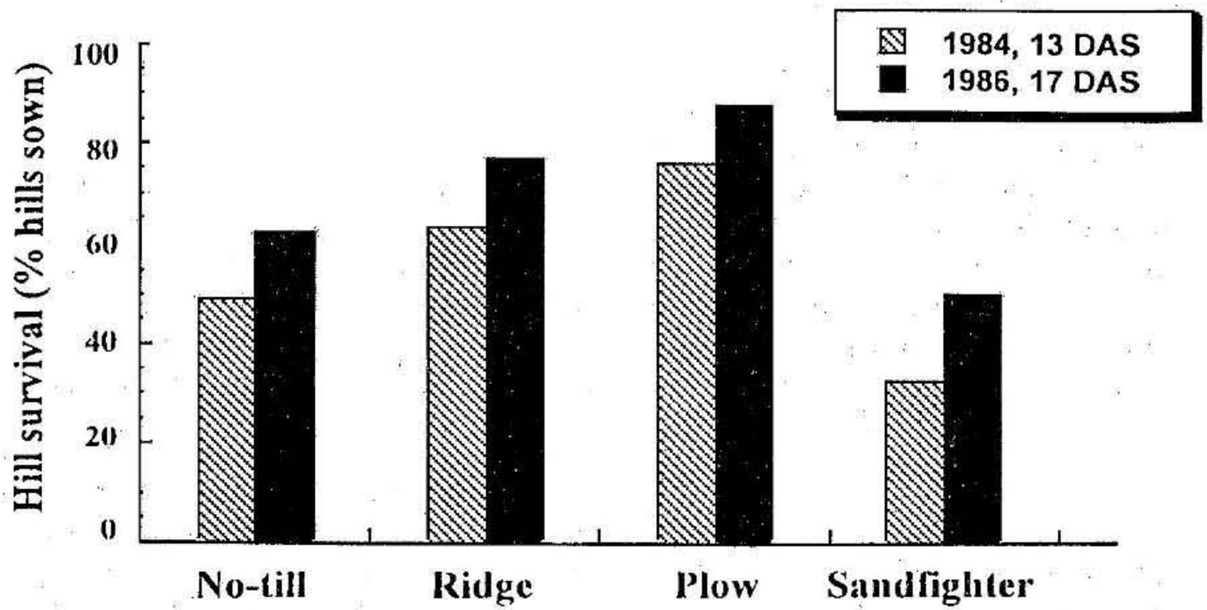

Figure 7. Hill survival as affected by primary tillage (Klaij and Hoogmoed 1993).

In a three year study, Leihner et al. (1993) did not find any yield response of millet to ridging compared to a no-till control in a low-windbreak system with spacing up to 90 m. On the contrary, cowpea produced significantly more dry matter and grain on ridged plots in two years out of three. The authors did not detect significant differences between ridged and no-till plots in terms of wind speed or total amount of wind-blown sand between 0.05 and 0.5 m above the ground. As the windbreak spacing was reduced from 90 to 6 m, larger reductions in soil flux were measured on no-till plots than on ridged plots. The absence of response to ridging in this experiment was attributed primarily to the low cloddiness of the sandy soil and weak cohesion of the ridges, making the ridges ineffective for erosion control. It is likely that the response of cowpea to ridging was not the result of better wind-erosion control but of improved soil physical conditions. The lack of response of millet to ridging went unexplained.

In an experiment conducted over three years to test the effectiveness of crop residue application and ridging on millet productivity and sand flux (Klaij, unpublished data), ridging was found to have consistently improved millet grain yield by an average of 80%. No positive effect of ridging on early millet stands was observed in two years out of three, but analysis did reveal that ridging significantly decreased sand flux at a 0.1 m height by an average of 26% over three years (Fig. 8). In the ongoing experiment at Banizoumbou, we measured a net soil loss of 16 t/ha in ridged plots in 1995, compared to a loss of 19 t/ha in bare plots for the period following ridge construction. Ridges were built perpendicular to the dominant easterly monsoon winds. In 1996, soil loss was 19 and 8 t/ha on bare and ridged plots, respectively. Despite the significant loss of topsoil, no overall decline in cowpea yield was observed over the two years. This is attributed to the particularly poor establishment of cowpea in 1995, irrespective of the treatment.

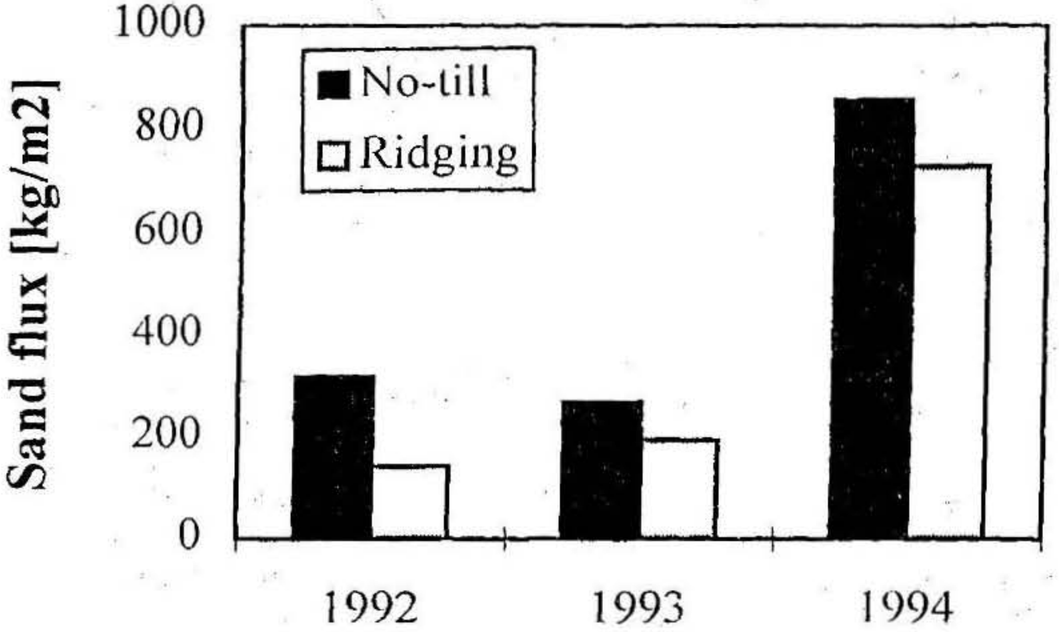

Figure 8. Annual sand transport measured at a height of 0.1 m as affected by ridging (Klaij, unpublished).

The use of a sandfighter—a shallow tillage operation used to increase surface roughness after each rainfall—did not improve plant establishment in one experiment and actually reduced early plant stands in another (Fig. 7; Klaij and Hoogmoed 1993). Final yield directly reflected this observation. The use of a sandfighter can therefore not be recommended for the weakly-structured sandy soils of the Sahel.

The results of the studies carried out at ISC over the last decade indicate large differences in response to ridging between experiments. This cannot be attributed solely to interannual variability. In a long-term experiment, ridged plots outyielded no-till plots in eight out of the last nine years (Klaij, unpublished data). Only in the first two years of this 11 year experiment was yield in the ridged plots lower than in the controls. Hence, some of the observed variability must come from site-specific conditions, which may be related to differences in the way the experiment was conducted or to external factors such as the degree of sheltering from wind effects. In order to clarify these observed differences, there is a need for a carefully designed experiment in which all relevant climatic, sand flux, and agronomic data are collected.

Vegetative barriers

To compensate for the fast-disappearing natural vegetation, it is a logical step to try to re-establish vegetative strips that can serve the purpose of reducing environmental degradation, increasing crop yield, and providing farmers with useful and sometimes marketable products. This line of thought has been pursued actively at ISC since the inception of wind erosion research at ICRISAT.

One can identify essentially three categories of windbreaks: windbreaks made up of perennial woody species (bushes or trees); windbreaks composed of perennial grasses; and mixed windbreaks. Banzhaf et al. (1992) and Leihner et al. (1993) report on the effectiveness of a windbreak made up of natural savanna vegetation, i.e., annual grasses approximately 0.6 m high, interspersed with scattered *Guiera senegalensis* bushes and the perennial grass *Andropogon gayanus*, 2.5 to 3m high. Compared to plots with windbreaks spaced 90 m apart, soil flux midway between windbreaks was reduced by 70% with 6 m spacing and by 53% with 20 m spacing (Banzhaf et al. 1992). Wind speed was reduced by more than 20% up to 10 m from the windbreak, i.e., up to 17 times the height of the grassy vegetation. In the last year of the experiment, early millet growth at the five leaf stage was increased by 90% when windbreak spacing was decreased from 90 to 6 m (Leihner et al. 1993). Data on this factor was not available for the first two years. This may indicate a beneficial effect of windbreak on yield through plant damage control, despite some evidence of increased competition for water at the narrower windbreak spacing. However, for all spacings, there was no significant effect of the windbreak on final millet yield in any of the three years of the experiment. This reflects the ability of millet to recover following initial poor growth.

Michels (1994) tested seven windbreak species during a two year study. All species were pruned to a height of 2 m and planted in double rows. Windbreak spacing was 30 m. Sand flux was measured only in plots with *Andropogon gayanus* and *Bauhinia rufescens* windbreaks. Sand flux was reduced by 25 and 58% over the two years for *A. gayanus* and *B. rufescens* windbreaks, respectively. A significant reduction in sand flux was measured, up to seven times the windbreak height for *B. rufescens*. For *A. gayanus* windbreaks, this effect was extended up to five times the height. Brenner et al. (1994) found that, in order to compensate for the loss of land allocated to the windbreak, and reduced yield close to the windbreak as a result of competition, the optimal spacing is 10–15 times the windbreak height. Hence, if this recommendation were to be followed, neither *A. gayanus* nor *B. rufescens* would provide adequate erosion control over the entire field. The difference between the results of Banzhaf et al. (1993) and Michels (1994), with respect to the windbreak zone of influence, is probably due to the use of different criteria for estimating the distance of influence.

For the two years of study, windbreak species did not have any effect on the number of hills buried under deposited sand, nor did Michels (1994) detect any effect of the distance from the windbreak on this factor. The authors argue that this may have been due to favorable climatic conditions related to the occurrence of sandstorms with respect to sowing. No consistent effect of windbreak on millet yield was observed over the two years. Some species tended to stimulate crop growth, while others depressed yield. Millet yield 1–3 m away from the windbreak was depressed by all species except *Faidherbia albida*, which is leafless during the rainy season. In accordance with the results of Banzhaf et al. (1992) and Leihner et al. (1993), the results of Michels' studies indicate that windbreaks are an effective means of controlling soil degradation through wind erosion. However, their effect on millet productivity is less clear-cut and subject to substantial variation. In terms of millet production, *F. albida* windbreaks were by far the most successful at increasing yield, even though the leafless nature of the tree in the rainy season probably makes it a poor windbreak, *per se*. The positive effect of this tree on its immediate surroundings is widely recognized, and can be attributed to changes in microclimatic conditions as well as in soil chemical fertility.

It has been shown that the profitability of windbreaks comes primarily from increases in millet yield. Nevertheless, the value of products derived from the windbreak species is an important determinant for their adoption. Data on the establishment, growth, and nutritional and calorific value of the seven species tested by Michels have been reported by Lamers et al. (1994) and will not be discussed here.

Andropogon gayanus is a grassy perennial species commonly found at the borders of farmers' fields and used for fodder and construction purposes. The value of this species for wind-erosion control was studied by Renard and Vandenbelt (1990) in a four year study. Ten meter wide strips of *A. gayanus* alternated with equally wide strips of millet. No data on sand flux were collected, but the authors measured a 15–20% reduction in wind speed in plots protected by *A. gayanus*. After a three year period, topographic measurements revealed a height difference of 150 mm between the *A. gayanus* strips and the unprotected plots, equivalent to 2,250 t soil/ha. Except in the first year, millet grain yield in protected plots tended to be depressed compared to unprotected plots. This may have been caused to some extent by competition for water, of which Renard and Vandenbelt (1990) showed some evidence. The authors recognized that the area of land dedicated to the *A. gayanus* borders in their experiment could not be recommended in practice. Nevertheless, they reckoned that, in view of the large amount of soil trapped by the grass, promoting the use of *A. gayanus* for field borders may provide an effective means of alleviating the soil degradation process in the Sahel.

Conclusions

A study carried out by Baidu-Forson and Ibro (1995) shows that farmers favor those wind-erosion control interventions that are low cost, simple to implement, and rely on local skills and inputs. On this basis, crop residue management probably comes closest to farmer expectation. Millet stover mulches are indeed occasionally used by Sahelian farmers for wind-erosion control, which can probably not be said for windbreaks and tillage. Based on the results presented earlier, the minimum rate under Sahelian conditions probably lies around 1.5–2 t/ha of millet stover in order to achieve effective soil loss and crop damage control. The widespread application of millet stover mulches at such rates is presently constrained by the low levels of productivity in Niger. Effective prevention of soil degradation through surface mulches will therefore require substantial productivity increases, achieved through the judicious integration of soil conservation measures with recommended management practices of organic and inorganic amendments, livestock, trees, and bushes.

As has been shown, windbreaks and tillage constitute effective alternatives for wind-erosion control under certain circumstances. However, as opposed to crop residue, the positive effect of these practices on millet productivity remains open to debate, and seems highly dependent on climatic and site conditions. Elucidating the reason for the large differences in response to tillage and windbreaks between experiments may require additional, carefully controlled experiments with comprehensive monitoring of all relevant factors. Nevertheless, under favorable circumstances, the establishment of windbreaks may help control wind erosion and therefore allow the use of lower levels of crop residue for mulching. Based on existing data, it is less evident that the combination of residue and ridging, or ridging and windbreaks, would enhance the effectiveness of either technique alone.

Several researchers have described the effect of sandblasting and burial on early millet growth and establishment. Except in the most severe cases, the studies show the remarkable ability of millet to recover from initial damage. Only seedling burial at specific early stages of millet development seems to significantly affect final yield, but the recurrence of such events is not known. Although interannual variability is high, the loss of topsoil by wind erosion is a continuous process which is much less sensitive to the timing of occurrence of the storm. As with water erosion, most soil is lost through a few intense storms. Although natural environments certainly show a significant resilience, it may take decades to restore the fertility of soil degraded by just a few sand storms. Soil degradation from wind erosion therefore constitutes a much stronger incentive for the large-scale implementation of erosion control techniques than the prevention of direct damage to crops.

Research Needs

Extensive research on wind erosion has been carried out by ICRISAT and advanced international research institutes at ISC and other parts of Niger. Although not reported here, a fair number of studies has also been dedicated to the understanding of constraints for implementation of wind-erosion control techniques as well as their financial evaluation (e.g., Buerkert et al. 1997). It is clear from these studies that none of the proposed techniques are quite suitable for immediate large-scale adoption under the prevailing socioeconomic conditions in Niger. Although improvements in this aspect may come from a shift in subsistence agriculture to a more market-oriented agriculture, there is scope for improving the technical aspects as well. In particular, there is a need to better integrate soil conservation technologies with soil fertility management practices into the current farming systems to make them more attractive to farmers. One option that deserves further investigation is the use of natural vegetation strips to trap wind-blown sediment and reduce wind erosion in adjacent fields. Even though natural vegetation may not be as effective as a dedicated windbreak, the establishment of natural vegetation strips would, in principle, answer some of the farmers' concerns in terms of low cost, ease of implementation, and local availability.

The data presented in the section on soil and nutrient loss clearly shows that there is a lack of reliable quantitative data on the severity of wind erosion in the Sahel. Only recently have there been attempts to quantify soil loss and deposition resulting from wind erosion. Indications are that soil loss could be even more substantial than sometimes expected, and by far exceed loss by water erosion. Collinet and Valentin (1985) show that the potential soil loss by water erosion of bare soil in sub-Saharan Africa steadily decreases from approximately 80 t/ha per year for the 2,000 mm rainfall zone in Côte d'Ivoire to 2 t/ha per year at the northern edge of the Sahel (150 mm rainfall). Perhaps the most reliable data so far presented on soil loss by wind erosion in the Sahel is by Sterk and Stein (1997), who measured losses of the order of 45 t/ha in just four storms. Similar results were obtained on-farm at Banizoumbou, Niger, in 1995/96. Even higher values have been reported by Buerkert et al. (1994), on the order of several hundreds of t/ha per year. Although some caution is required in using this latter data to estimate the extent of wind erosion, it points to the fact that wind erosion constitutes a much larger threat to the soil resource than water erosion in the Sahelian zone. There is thus an urgent need to better quantify soil and nutrient flux resulting from the erosive action of wind under on-farm conditions. Besides more intensive monitoring, the quantification of the impact of wind erosion on soil and nutrient budgets will require methodological developments for more accurate measurement of wind-blown sediment, particularly with respect to the dust fraction, which is inherently richest in nutrients, and transport by surface creep, which may contribute significantly to the development of field-scale variability.

In addition to the evaluation of present mass and nutrient transfer by wind, the effect of changes in land use on soil and nutrient budgets, and on long-term productivity, must be quantified. One first step is the establishment of a potential wind-erosion risk map based on soil properties, and, wherever possible, wind characteristics. Steps have already been taken towards this goal. Estimates of actual wind erosion will require integration of information on vegetation and land use. After appropriate calibration, models could be used to predict soil loss by wind erosion for certain combinations of soil, vegetation, and land use. The same approach could then be used to estimate the effect of changes in land use, or of the aridification of the climate observed over the last two decades (Sivakumar et al. 1993).

In the Sahelian zone, land degradation does not only take place through wind erosion. Overgrazing, nutrient mining, and water erosion all contribute to the overall impoverishment of the environment. At present, to the authors' knowledge, there have been no attempts to study the interactions between these major soil degradation processes. For instance, it is readily apparent in existing trials that wind erosion increases the aerial extent of erosion crust by removing the loose sandy material that forms the surface of structural crusts. Erosion crusts are the least permeable of the crust types identified by Casenave and Valentin (1989). Herrmann et al. (1994) present evidence that crust formation may actually be enhanced by the deposition of dust particles during the harmattan and early wet season. By inducing a segregation of particles at the surface, raindrop impact during storms leads to the accumulation of the sand fraction at the soil surface (Bielders and Baveye 1996), a fraction that is highly sensitive to wind erosion. One can already see close interactions between the processes of crust formation, wind erosion, and water erosion. Besides the effects of water erosion, we need to be able to separate the effects of nutrient mining and wind erosion on nutrient depletion in the soil. Interactions between overgrazing and wind erosion occur mainly through the changes in vegetation induced by high grazing activity and the disturbance of the soil surface. Hence, there is a clear need to begin studying the interactions between various degradation processes to better quantify present and future land degradation and identify appropriate means to halt desertification.

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