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Wind Erosion Control Technologies in the West African Sahel: The Effectiveness of Windbreaks, Mulching and Soil Tillage, and the Perspective of Farmers

Charles L. Bielders[1], John P.A. Lamers[2] and Karlheinz Michels[3]

[1] *Department of Environmental Sciences and Land Use Planning, Université catholique de Louvain, Louvain-la-Neuve, Belgium*

[2] *Centre for Development Research (ZEF), University of Bonn, 53113 Bonn, Germany*

[3] *Institute for Plant Production and Agro-Ecology in the Tropics and Subtropics, University of Hohenheim, 70593 Stuttgart, Germany*

Abstract: Wind erosion constitutes a major threat for the sustainable use of land resources in the Sahel. It is favored by a long dry season, low vegetation cover, sandy soils and the occurrence of strongly erosive winds at critical times of the year. Wind erosion can result in considerable losses of soil and nutrients at the plot and field scale and impart significant damage to crops through sand blasting and seedling burial. Current land management such as land clearing practices also largely favors the occurrence of wind erosion, forcing farmers to actively implement conservation measures that reduce the potential impact of wind erosion. As a rule, such measures need to be low cost, rely on local skills and knowledge, and typically present multiple benefits besides wind erosion control such as soil fertility improvement or the production of products for household consumption. The present paper reviews the current knowledge about the extent and severity of wind erosion in the Sahel at scales up to village land units, and discusses some of the technological options that are available to farmers for reducing the impact of wind erosion on agricultural land. Emphasis is laid both on the technical and socio-economic feasibility of the techniques.

Key words: Sahel, farmer perception, wind erosion, windbreak, tillage, mulching.

Bordering the Sahara Desert on its southern fringe, the Sahel region spreads over 6000 km from east to west across the African continent (Fig. 1). Meaning 'shore' in Arabic, it extends southward from the Saharan sand seas over a distance of 400 to 600 km towards the more humid tropical zones. With a long term average annual rainfall of 200 to 600 mm, the Sahel falls within the major semi-arid areas of the world and, as such, it is characterized by the occurrence of a prolonged dry season, and by high rainfall with spatial and temporal variability, leading to frequent drought spells.

About 30% of the world's strongly degraded land is located in the Sahel (Le Houerou, 1989). In this region, a gradual increase in the atmospheric dust load has been monitored over the last several decades (Coudé-Gaussen, 1994; Valentin, 1994), reflecting the progress of desertification. Causes of land degradation in the Sahel have been linked to rapid demographic changes (Mainguet, 1999). Wind erosion is both a major contributing factor to land

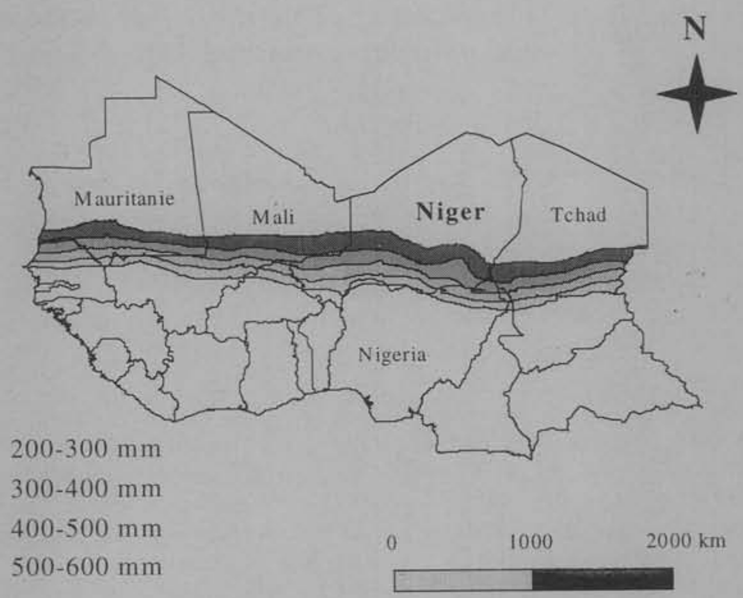

Fig. 1. Location of the Sahelian zone in West Africa between the 200 and 600 mm annual rainfall isohyets.

degradation and a consequence of desertification (Mainguet and Chemin, 1991; Sivakumar *et al.*, 1998). Indeed, the conversion of savannah into cropland, the loss of soil fertility as a result of nutrient mining, overgrazing and the overexploitation of natural vegetation increase the risk of bare soil being exposed to the erosive action of the wind. Because most nutrients in the inherently low fertility soils of the Sahel are concentrated in the topsoil, wind erosion in turn results in the loss of proportionally large quantities of nutrients, thereby exacerbating soil fertility decline and ultimately hampering vegetation development.

Wind erosion is commonly associated with the presence of dunes. In sub-Saharan Africa, however, the zone of active dunes lies north of the Sahel in the annual rainfall zone of <100 mm (Cooke *et al.*, 1993). Consequently, wind erosion in the Sahel threatens the sustainable use of the land resources not because of sand invasion, but because of its effects on soil fertility, crop production and human health.

Analyses based on the nature of sand formations in the Sahara and its Sahelian fringe indicated that most of the Sahel is a zone of net deposition of wind-transported material (Mainguet, 1990) although locally negative sediment balances have been inferred from soil particle size data (Mainguet and Chemin, 1991). Valuable as it is, such a large-scale approach does not provide information on wind-mediated land degradation at the scale of fields or village land units which directly affects the livelihood of the local population. Indeed, wind erosion is particularly important on cropland since climatic conditions and land management practices result in the soil being left bare for most of the year. Wind-mediated transfer of soil and nutrients may not only exacerbate the yield decline initiated by nutrient mining practices, 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. This may have important repercussions for crop production and for the subsistence farmers living off their land (Sterk *et al.*, 1996). It is, therefore, essential that technologies be developed and promoted that can reduce the severity of soil and nutrient losses at the local scale, i.e., on cultivated fields.

Following an overview of the production environment and of the extent and severity of wind erosion in the Sahel, the present review focuses on wind erosion control technologies from a technical as well as social and economic viewpoint. Although targeting the entire Sahelian zone of West Africa, this review draws extensively on the case of Niger in the middle of the Sahel, where research and development organizations have gained much experience and knowledge over the last few decades.

Production Environment

Climate

The climate in the Sahelian zone of Niger is to a large extent influenced by the seasonal fluctuations of the Intertropical Convergence Zone (ITCZ). Rainfall generally follows the passage of the ITCZ with most rainfall falling between June and September. Annual rainfall ranges from 200 mm in the northern Sahelian zone to 600 mm at its southern limit with a length of growing period comprized between 75 and 125 days. Rainfall is highly variable in time and space, and often comes in the form of convective storms (Sivakumar *et al.*, 1993). In Niger's capital Niamey, average monthly maximum (daytime) temperatures range from 33°C in January to 41°C in April. Potential evapotranspiration (PET) exceeds rainfall by a factor 2 to 20. At Niamey, PET amounts to 2290 mm per year and exceeds rainfall in all months except August (Sivakumar *et al.*, 1993).

In the Sahel, two main periods of importance with respect to wind erosion have been identified (Michels *et al.*, 1995b). From December to March, north-easterly Harmattan winds result in the transport and deposition of dust-size particles from the Sahara towards the Sahel. These winds, which seldom exceed 8 m s^{-1}, but last for several days, can also lead to the re-entrainment of local sediment (Rajot, 2001). The second period, which starts in April and goes well into the rainy season (July), is characterized by the occurrence of south-easterly monsoon winds and easterly dust storms. After the start of the rainy season, these dust storms are usually followed by heavy rainfall. Whereas the monsoon winds are of moderate intensity, but may last for several hours, dust storms typically last less than one hour with mean wind velocities up to 15 m s^{-1} (Bielders *et al.*, 2000; Michels *et al.*, 1995b). Total sand fluxes during the dry season measured at 0.1 m above the soil surface constitute less than 15% of the total annual sand fluxes (Fig. 2) (Michels *et al.*, 1995b).

Soils and vegetation

The soils in the Sahelian zone are dominated by Entisols and Alfisols (Bationo

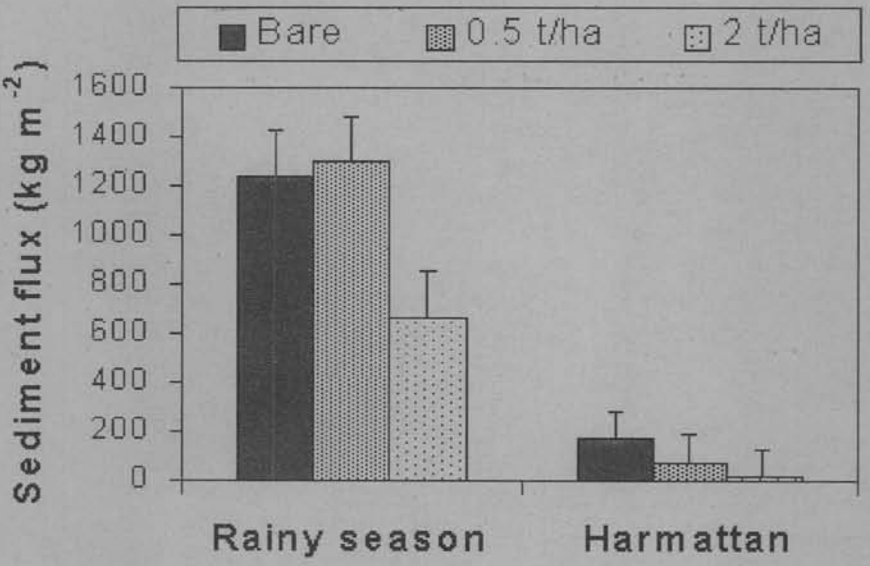

Fig. 2. Effect of millet stover mulching rate on total sediment fluxes 0.1 m above ground during the rainy season (June-Aug. 1991) and the Harmattan season (Dec. 91 - April 92). Error bar = LSD at the 5% probability level (after Michels et al., 1995b).

et al., 1997). Both soil types typically have a sand content greater than 80%, low organic matter content (0.5 to 1.5%), low water holding capacity and are poorly aggregated, rendering them particularly sensitive to surface crusting, wind and water erosion. In Niger, Arenosols - deep sandy soils of aeolian origin - occupy by themselves 43% of the land used for agro-silvopastoral activities in Sahelian zone (FAO, 1973).

The rainfall and temperature regime of the Sahel determine the development of an open grass Savannah in the north, with scattered bushes and trees in the south. Many of the trees and bushes are drought-deciduous. At the end of the dry season, the ground vegetation cover is usually very sparse as a result of the prolonged dry season, termite activity and grazing by livestock.

Socio-economic conditions

Although very diverse, the Sahelian countries of West Africa are characterized by high annual growth rates (2.4 to 3.1%) of population, a low gross domestic product per capita (less than US$ 500), and a fragile agricultural sector. Even though total food production has increased over the last few decades, food production per capita has declined since 1980 in some Sahelian countries, and by up to 30% in Niger. Niger, Mali and Burkina Faso all rank in the lower 10% of the Human Development Index of the United Nations (UNDP, 2001).

The major part of the Sahelian population depends on agriculture. A key element of the national development plans is an increase in cereal production and in the export of agricultural commodities such as livestock, cowpea, cotton and groundnut. The agricultural sector employs most of the country's labor force and accounts for at least 30% of the gross domestic product.

Although rural incomes are highly diversified (cropping, agricultural wage, livestock husbandry, commerce, service, transport, construction, food preparation, gathering, crafts, migration) the agricultural sector is the spearhead of the rural economy. Nevertheless, non-farm income sustains the livelihood of farmers, assures food security, and provides liquidity for investments.

Farming systems

Decision-making by Sahelian 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. In the <350 mm annual rainfall zone, pastoral activities dominate. In the more humid areas of the southern Sahelian zone (350-600 mm annual rainfall), agricultural production relies on both rainfed cropping and livestock, with close ties between the two.

Dryland agriculture in the Sahel is dominated by sole pearl millet or millet-based intercropping. In Niger, for instance, millet-based cropping systems occupy 90% of the agricultural land. Because of low external inputs and the harsh environmental conditions, millet yields are invariably very low, generally less than 600 kg grain ha^{-1} in most Sahelian countries. In Niger over the 1989-1991 period millet yields averaged 340 kg grain ha^{-1} and approximately 1200 kg straw ha^{-1} (Baidu-Forson and Williams, 1996).

In rainfed agriculture, the use of chemical fertilizers is low. Fertilizer application recommendations have found little acceptance by subsistence farmers because the profitability of these chemical fertilizers is constrained by the high fertilizer cost and low coarse grain prices (Bruentrup *et al.*, 1996), as well as by the unpredictability of yield increases with the application of these fertilizers in relation to rainfall variability. As a result, average fertilizer use ranges from less than 1 kg ha^{-1} for Niger to 8 kg ha^{-1} in Mali and Senegal. Soil fertility restoration is achieved primarily by leaving the land fallow after an extended period of cultivation. Because of demographic pressure, the duration of fallow has, however, been reduced considerably. Although commonly practised, the amendment of cropland with livestock faeces is frequently restricted to selected low fertility spots in fields because of limitations in terms of the quantities available (Schlecht *et al.*, 1995).

The mixed-farming systems (crop/livestock) are based on limited family labor and low budgets, which are largely depleted by hiring labor, mostly for weeding. Most households keep some sheep, goats, and sometimes cattle. The use of animal traction is limited to its use for transport with bulky carts. Millet stover is a valuable and critical resource in the crop/livestock systems. During the dry season, hay from pulses, grasses, and fodder weeds enrich the millet stover-based diet of animals.

On the sandy soils, land preparation is limited to the clearing of vegetation and sometimes burning of remaining crop residues, and weeding. All cropping activities are performed manually using hand-held tools. On the finer-textured Alfisols, shallow tillage is more commonly practised using hand-held hoes or animal-drawn implements.

Millet is generally sown with the first rain exceeding 15 mm. The low planting densities (3000-5000 hills ha^{-1}) and low levels of surface residue leave the soil of cropland with little or no protection against wind erosion until 6 to 8 weeks after the start of the rainy season. At the start of the rainy season residue levels seldom exceed 500 kg ha^{-1} as a result of grazing, decomposition by termites or its use as construction or fencing material (Lamers and Bruentrup, 1996). The traditional sowing practice, which consists of throwing 20 to 40 seeds into a shallow hole dug with a hand-held hoe before closing it with the foot, creates small depressions which favor sand accumulation and the burial of the seedlings under certain conditions.

Impact of Wind Erosion

Soil and nutrient loss

Although wind erosion is by no means a recent phenomenon in the Sahel, western scientific interest in wind erosion dates back to the late colonial period. The occurrence of wind erosion during the dry season as a result of north-eastern winds was noted by Aubert *et al.* (1947) in Mali and Senegal. Dugain (1960) reported wind erosion to be a problem in Niger.

At the regional scale, wind erosion results essentially in the loss of fine dust particles carried in suspension over sometimes considerable distances. Middleton *et al.* (1986) estimated that 260 million tons of dust-size particles are removed each year from the Sahara-Sahel region. Such massive dust emissions have significant repercussions on the global energy balance with consequences, for instance, on the frequency of hurricanes on the east coast of the United States (Prospero, 1999b) and on the nutrient cycle in the Amazon basin. Because the Sahara and the Sahel relate to the same global wind action system (Mainguet, 1998), it is difficult, however, to specify the relative contribution of the Sahel to the dust emission of the Sahara-Sahel region.

Current estimates of the extent of wind erosion in the Sahel largely rely on expert knowledge rather than on quantitative assessments. In the Sahel, approximately 256 million hectares are thought to be affected by light or moderate wind erosion, representing one-third of the land area. Another 6 million hectares are strongly to extremely severely affected by wind erosion (Middleton *et al.*, 1997). Not withstanding the usefulness of this subjective approach to provide a first, rough estimate of the extent of wind erosion damage to the land resources, few direct measurements of wind erosion are currently available for validation of the expert assessments.

Results of soil mass balance calculations at various scales are presented in Table 1. Assuming that particles >20 μm are not subject to long range transport, Rajot (2001) recently estimated that, under present land use conditions, the mass balance for an area 25 x 25 km in size in Western Niger was positive at 0.36 t ha^{-1} y^{-1}. This is in contrast with the results of Chappell *et al.* (1998a, b) who, using the ^{137}Cs methodology, reported soil losses ranging between -16 and -48.5 Mg ha^{-1} y^{-1} over a 30-year period, averaged over a 0.5 km^2 study area also in Western Niger. Given that the extent of erodible cultivated land has been increasing

Table 1. Wind erosion-induced sediment mass balances at various scales in Western Niger

Scale	Mass balance	Method	Remarks	Reference
Experimental plot	$-46\ t\ ha^{-1}$	Horizontal sand fluxes measured using Wilson and Cook sand catchers	From 4 sandstorms, 2400 m^2 plots	Sterk and Stein, 1997
Experimental plot	-12 mm (190 $t\ ha^{-1}$)	Elevation difference	Plots affected by water erosion, 11-month period	Buerkert and Lamers, 1999
Experimental plot	$>-51\ t\ ha^{-1}$	Horizontal sand fluxes measured using BSNE sand traps	300 m^2 plots from 16 sandstorms	Bielders *et al.*, 2000
Experimental field	$+5\ t\ ha^{-1}$	Horizontal sand fluxes measured using BSNE sand traps	8 ha field, 1st year of cultivation, 15 May - 15 Sept.	Bielders *et al.*, 2001
	$-6\ t\ ha^{-1}$		2nd year of cultivation	
	$-26\ t\ ha^{-1}$		3rd year of cultivation	(unpublished)
Village land unit	$+0.36\ t\ ha^{-1}\ y^{-1}$	Mass balance of particles < 20 m based on measured and estimated vertical fluxes	25 x 25 km area, average over 3 years	Rajot, 2001
Landscape	$-48.5\ t\ ha^{-1}\ y^{-1}$	^{137}Cs	0.5 km^2 area, mean value over last 30 years	Chappell *et al.*, 1998a
Landscape	$-16\ t\ ha^{-1}\ y^{-1}$	^{137}Cs	0.5 km^2 area, mean value over last 30 years	Chappell *et al.*, 1998b

in the study area over the last 30 years, but represented only 41% in 1997 (Loireau *et al.*, 2000) and that the ^{137}Cs methodology cannot effectively discriminate between wind and water erosion, it is likely that the results of Chappell *et al.* (1998a, b) grossly overestimate the actual soil losses by wind erosion. Mainguet and Chemin (1991), however, have also inferred negative sediment balances for certain areas of the Sahel based on particle size data.

Plot-scale estimates of soil and nutrient losses by wind erosion have generally been based on the measurement of changes in surface elevation over time or on the changes in horizontal mass flux of airborne sediment with distance. Whereas the latter is solely correlated with wind erosion, the former may be affected by other processes such as changes in soil bulk density or water erosion.

Geiger *et al.* (1992) and Michels *et al.* (1995b) reported on relative differences in surface elevation of bare plots compared to mulched plots. Because such measurements reflect both deposition in mulched plots and erosion in bare plots, they cannot be interpreted in terms of a net soil mass balance. Buerkert and Lamers (1999) carried out repeated measurements of surface topography over time on experimental plots during an on-station trial in Niger. Over an 11-month period, these authors observed a change in surface elevation on bare millet plots of -12 mm, equivalent to a soil loss of about 190 t ha^{-1}. The experimental site, however, favored water erosion and the measured changes in surface elevation may, therefore, not result solely from wind erosion.

Following intensive monitoring of soil mass fluxes in an experimental plot covered with a 0.8 t ha^{-1} millet stover mulch, Sterk and Stein (1997) reported a total loss of -45.9 t soil ha^{-1} from four convective storms in western Niger. Soil losses of similar magnitude were reported by Bielders *et al.* (2000) for an on-farm experiment. These authors estimated the soil losses on bare plots to be in excess of -57 t ha^{-1} y^{-1} for a 3-year period.

For the aforementioned experiment Sterk *et al.* (1996) reported a total loss of 57.1 and 6.1 kg ha^{-1} of K and P, respectively. These amounts are roughly equivalent to the quantity of K and P required to produce a millet yield of 2000 kg straw and 600 kg of grain ha^{-1} (Bielders *et al.*, 1998). Over the same time period Sterk *et al.* (1996) measured nutrient inputs of 2.5 and 0.2 kg ha^{-1} of K and P, respectively, from dust deposition.

Although the above studies provide conclusive evidence of the potential severity of field-scale wind erosion in the Sahel, all results are derived from controlled field experiments, which seldom reflected the management practices of small-holder farmers. Indeed, the studies invariably involved higher planting densities as well as better and more timely crop management operations than would be the case at the farmer level. In addition, they frequently involved crop residue mulching rates which can only with difficulty be met by farmers and sometimes also included the use of mineral fertilizers. Bielders *et al.* (2001b) evaluated the severity of soil losses by wind erosion in a farmer-managed, 8 ha field in western Niger. In the first year of cultivation after a long term fallow, these authors reported soil deposition rates of the order of 5 t ha^{-1} during a 3-month period from mid-May to mid-August. This reflected the trapping of sediment from surrounding fields by the surface litter cover. For the same period of the year, a soil loss of 5 t ha^{-1} was measured in the second year of cultivation. In the third year, losses of the order of 25 t ha^{-1} were measured (unpublished). These results demonstrate a gradual increase in the erodibility of cultivated land and the danger of extrapolating plot-scale measurements from controlled plot-scale experiments to farmer-managed cultivated fields.

Crop damage

Direct damage to crops during sandstorms can result from the loss of plant tissue and reduced photosynthetic activity as a result of sandblasting. In addition, deposition of windblown sediment may lead to seedling burial. Because millet is the first crop to be sown at the start of the rainy season, this crop is particularly exposed to sandblasting damage and seedling burial. Past studies on crop damage in the Sahel have therefore concentrated on this crop.

On the basis of wind tunnel studies, Michels *et al.* (1995a) reported a high tolerance of millet against sandblasting damage compared to other crops (Armbrust, 1982; Fryrear, 1971; Fryrear and Downes, 1975). Sandblasted plants had their viable leaf area and photosynthetic activity reduced, but under optimal conditions, millet recovered well from the leaf damage. This finding was in line with the results of Brenner (1991) obtained under field conditions.

A consequence of the method of sowing millet in holes is the burial of seedlings under deposited wind-blown sand. This sometimes necessitates partial or total resowing of the crop. Michels *et al.* (1993) reported that 90% of millet pockets in a traditionally sown experimental field required resowing after a severe sandstorm. Even partial seedling coverage by sediment may significantly affect seedling development. According to Michels *et al.* (1993), final grain yields from plants that had been partially covered at the seedling stage were reduced by half compared to plants that had not been buried. One may, therefore, conclude that seedling burial constitutes the main direct constraint for crop growth as compared to sandblasting damage.

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 extent depend on the strength and timing of sandstorms with respect to the time of sowing. Furthermore, the evidence indicates that decisive damage may occur when several sources of stress are combined, as is frequently 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 days after emergence by 47% compared to unexposed buried plants (Fig. 3; 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.

Farmer Perception of Wind Erosion

Various household surveys have been conducted to learn about farmers' awareness and knowledge on wind erosion (Baidu-Forson and Napier, 1998; Bielders *et al.*, 2001a; Feil and Lamers, 1996; Lamers *et al.*, 1995; Sterk and Haigis, 1998). In general farmers view wind erosion as a vicious cycle that is originally initiated by decreasing soil cover and yield. Reduced stover yield means less mulching material, which leaves the topsoil layer exposed to wind erosion.

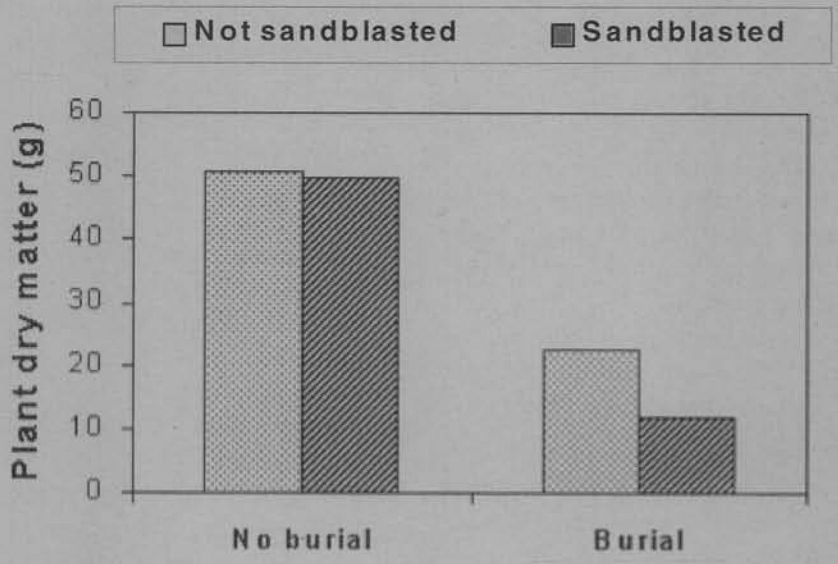

Fig. 3. Effect of sandblasting and seedling burial on the dry matter of millet plants 70 days after emergence. Plants were exposed 2 to 8 days after emergence to a sand flux of 25 g m^{-1} s^{-1} for 15 min. prior to being buried under 15 mm of soil (after Michels et al., 1995a).

Based on a survey of 41 villages in the southern Sahelian zone of Niger (400-600 mm annual rainfall), Bielders *et al.* (2001a) reported that farmers viewed wind erosion as a moderate to high constraint for agricultural production in 39% of the surveyed villages (Fig. 4). Wind erosion ranked 8th overall as a constraint for agricultural production, but ranked third among environmental constraints, behind drought and low soil fertility. Wind erosion appeared to be of greater concern to the surveyed communities in the higher rainfall areas than in the drier areas. In the drier areas, other constraints such as drought, famine and poverty, insect pests and soil fertility are of such overriding importance that wind erosion becomes a secondary issue, despite the fact that wind erosion should in principle be more pronounced in these areas. On the basis of a survey of 24 villages in the 400 mm annual rainfall zone, Baidu-Forson and Napier (1998) similarly concluded that farmer participation in wind erosion control programs may be hampered by the low perceived importance of wind erosion compared to other constraints.

In 93% of the villages surveyed by Bielders *et al.* (2001a), farmers felt that wind erosion was increasing over time. A similar finding was reported by Sterk and Haigis (1998) for villages where wind erosion control measures had not been implemented in the past. This agrees with observations of increasing number of dusty days over the last decade (Valentin, 1994). Dust- related

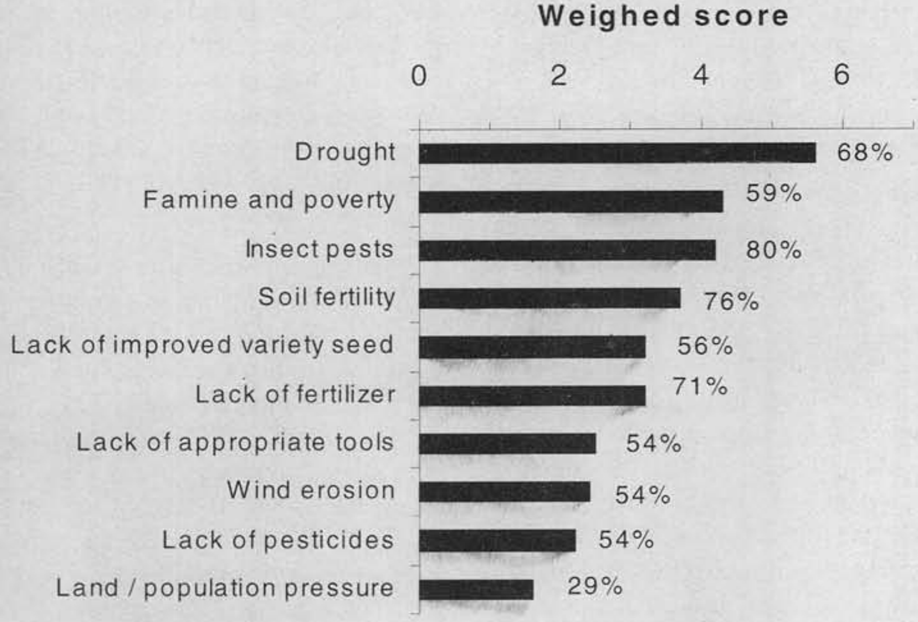

Fig. 4. Ranking of constraints to agricultural production as perceived by male farmers in 41 villages across Niger. Constraints are scored on a scale from 0 (low constraint) to 9 (high constraint). Percentages refer to the percentage of villages mentioning a given constraint (after Bielders et al., 2001).

health problems were of most concern in 78% of the villages surveyed by Bielders *et al.* (2001a). Health problems, including coughing, sore eyes and fever, were mainly related to Harmattan periods and to a lesser extent to the period of convective storms. The impact of airborne dust on health has been well-documented elsewhere (Prospero, 1999a). Soil and crop damage were rated nearly equally by villagers (Bielders *et al.*, 2001a). A real damage is perceived by farmers when the top layer is removed and when the subsequent formation of a surface crust prevents water infiltration (Feil and Lamers, 1996; Lamers *et al.*, 1995). Farmers observe soil losses due to wind each year and on most fields, but soil erosion is considered harmful on specific patches within a field only.

Farmers are well aware of the impact of their land management practices on wind erosion (Bielders *et al.*, 2001a). These include deforestation, land clearing and removal of crop residue. In particular, the burning of fields was recognized as favoring wind erosion. On the other hand, grazing by livestock and climatic factors were not viewed as important determinants of wind erosion, an observation that is consistent with the results of Baidu-Forson and Napier (1998). Although soil loss by wind erosion results in a loss of fertility, farmers also recognized the fact that wind-blown sediment deposition enhances soil fertility and crop productivity (Feil and Lamers, 1996; Sterk and Haigis, 1998).

Wind Erosion Control Technologies

As early as 1965, Raulin (1965) emphasized the need for wind erosion control in Niger and advocated the use of tillage, mulching and field borders made from natural vegetation. In Niger conservation measures were initiated in the 1960's, but these were initially mostly geared towards sand encroachment using mechanical or biological dune fixation techniques (Ben Mohammed, 1998). Although spectacular, sand encroachment is only of secondary importance in the Sahel compared to the loss of windblown soil and nutrients and crop damage. In the following, only techniques designed to control soil loss and crop damage will therefore be discussed.

Wind erosion control measures are generally classified into three categories: mechanical tillage operations, crop or residue management practices, and vegetative barriers. In the end, all 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 in the Sahel on all three types of wind erosion control measures.

Crop residue management

Crop residue management is probably one of the most discussed alternatives for wind erosion control in a resource-poor environment such as the Sahel. Extensive research has, therefore, been carried out on the use of millet stover mulches for improving plant stand establishment and reducing soil losses, in view of defining optimal application rates and appropriate crop residue management strategies.

Reductions in windblown sediment fluxes at 0.1 m aboveground in the order of 42 to 56% have been reported in the presence of a 2 t ha^{-1} millet stover mulch as compared to unmulched plots (Buerkert, 1995; Michels *et al.*, 1995b). This application rate corresponds to a surface cover of between 7 and 10%. On the basis of repeated measurements of surface elevation, Buerkert and Lamers (1999) reported a net deposition of 270 t soil ha^{-1} (17 mm) over an 11-month period. Geiger *et al.* (1992) reported that relative height differences of 150 mm developed over a 5-year period 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 the mulched plots. Bielders *et al.* (2000) reported potential sediment deposition rates in excess of 16 t ha^{-1} over a two year period on on-farm experimental plots mulched at a rate of 2 t ha^{-1}.

Compared to unmulched plots, no significant reduction in soil flux was measured with a 0.5 t ha^{-1} mulch application except during the weakest storms of the Harmattan period (Michels *et al.*, 1995b). Following this work, Sterk and Spaan (1997) tested two intermediate application rates of mulch, namely 1 and 1.5 t ha^{-1}. These authors observed a tendency for the effectiveness of crop residue mulches to decrease with increasing wind velocity. For wind velocities ranging from 8.3 to 10.6 m s^{-1}, the mass flux reduction efficiency dropped from 80 to 50% at the mulching rate of 1.5 t mulch ha^{-1}. Similar observations were also reported by Michels *et al.* (1995b), who observed that the efficiency of millet stover for reducing soil fluxes was higher during the dry season than during the rainy season. This was attributed primarily to the lower average wind speeds that characterize the Harmattan winds. Sterk (2000) explained the reduction of the millet stover mulch efficiency by increased turbulence at high wind speeds. In extreme cases and at low mulching rates, mulching may exacerbate wind erosion compared to unmulched plots (Sterk and Spaan, 1997).

Bielders *et al.* (2000) evaluated the application of a millet stover mulch at a rate of 2 t ha^{-1} applied either in 0.3 m wide bands spaced 1.5 m apart or broadcast homogeneously across the plots. They reported that for wind directions approximately perpendicular to the residue bands, the sediment trapping efficiency of both application methods was similar. However, because the trapping efficiency of broadcast residue is expected to be independent of wind direction as opposed to banded residue, these authors did not recommend the use of banded residue for wind erosion control.

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 a 2 t ha^{-1} millet stover application rate. No significant difference in terms of seedling burial could be found between a 0.5 t ha^{-1} mulching rate and the bare controls over the two years of their study. Final yields 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.

Based on the soil flux and seedling burial data presented above, it is clear that an application rate of 0.5 t ha^{-1} 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^{-1} application rate compared to 1 t ha^{-1}, Sterk and Spaan (1997) recommended the use of the higher application rate for wind erosion control purposes. This rate is at the same time somewhat more accessible to farmers than the 2 t ha^{-1} rate tested by many researchers. It is not known whether this rate would also provide suitable protection to seedlings against burial. The data of Michels *et al.* (1995c) indicate that even at a rate of 2 t ha^{-1}, the protection against burial is only partial.

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 production 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 yields, tillage is not widely practised on the sandy Arenosols of the Sahelian zone. Tillage may nevertheless constitute 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 3-year experiment Klaij and Hoogmoed (1993) showed that early plant establishment was highest for plowed soil, followed by ridging and no-till plots. 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 were essentially identical for ridged and no-till plots. On the contrary, plowed plots consistently maintained a higher plant density than the other treatments. In normal rainfall years, ridging and plowing improved millet yields 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 western Niger the effect of plowing on surface roughness is rather short-lived. The beneficial effects 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 longer and may therefore be more effective at reducing soil fluxes during the most critical, millet establishment phase. In addition it is likely that planting on top of the ridge also prevents seedling from burial, although this has not been documented. In an 11-year experiment at a site that was sheltered against the effect of wind, ridging and plowing consistently improved millet grain and straw yields, but the yield advantage of ridging in this case was of the order of 10% only (Klaij, unpublished). It is therefore 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 are presently available to support this assertion.

In a 3-year study, Leinher *et al.* (1993) did not detect significant differences between ridged and no-till plots in terms of wind speed or total amounts of wind blown sand between 0.05 and 0.50 m above the ground. They did not find any yield response of millet to ridging compared to a no-till control. On the contrary, cowpea produced significantly more dry matter and grain on ridged plots in two years out of three. The absence of response of millet to ridging in this experiment was primarily attributed to the low clodiness of the sandy soil and weak cohesion of the ridges, making the ridges ineffective for erosion control purposes. 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.

Klaij (unpublished) specifically designed an experiment to test the effectiveness of crop residue applications and ridging on millet productivity and sand fluxes. In contrast to the results of Leinher *et al.* (1993), ridging significantly decreased sand fluxes at 0.1 m height by an average of 26% and consistently improved millet grain yields by an average of 80% over the three years of the experiment. However, no positive effect of ridging on early millet stands was observed in two years out of three.

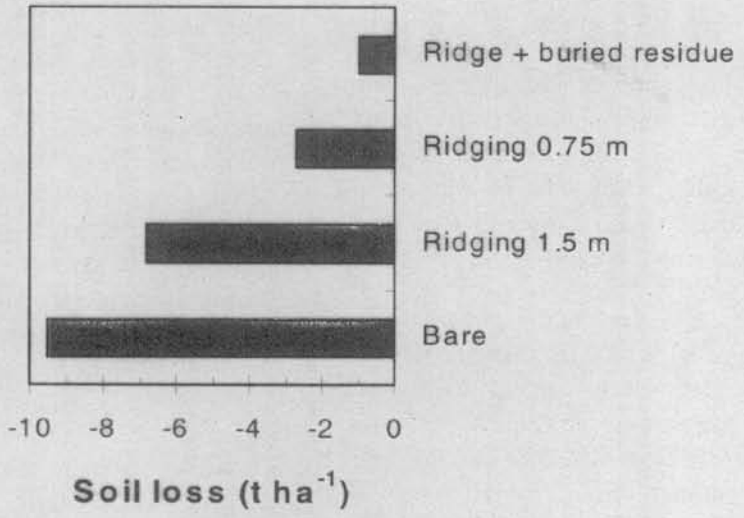

Fig. 5. Effect of ridge spacing and burial of millet stover in ridges on total soil loss from four consecutive storms, Niger 1995 (after Bielders et al., 2000).

In an on-farm experiment, Bielders *et al.* (2000) evaluated the effectiveness of 0.2 m high ridges spaced 1.5 m apart. They reported that ridges approximately perpendicular to the wind direction reduced soil erosion rates on an average by 57% on average over a 3-year period compared to bare plots. However, this average effectiveness masked a rapid decline in the erosion reduction efficiency of ridges under the influence of rainfall, soil translocation and weeding. After 100 mm of rainfall, the erosion rate on ridged plots was only 15% lower than on bare plots. Reducing the ridge spacing from 1.50 to 0.75 m increased the effectiveness of ridges. Compared to control plots, ridging at 0.75 m and 1.50 m spacing reduced soil losses by 89 and 28%, respectively, over 4 sandstorms (Fig. 5). The efficiencies reported here relate to sandstorms with wind directions approximately perpendicular to the ridges. For other wind directions, the efficiency is expected to drop rapidly (Fryrear, 1984).

Because of the rapid collapse of ridges on the sandy soils, burial of millet stover in ridges may act as a stabilizing agent and extend the useful life of ridges. Bielders *et al.* (2000) reported that this practice reduced soil losses by 87% on an average over 3 years compared to bare plots, whereas ridges without buried residue reduced losses by only 57%. As opposed to the conventional ridges, the efficiency of ridges with buried residue did not decrease over time under the influence of rainfall. An added benefit of the ridge with buried residue technique is that they can be built soon after harvest, thereby providing soil protection throughout the dry season and without affecting their effectiveness during the subsequent cropping season (Bielders *et al.*, 2000). This may constitute an advantage since the large-scale implementation of ridging will require the use of animal traction, and animal draught power will be higher at the end of the rainy season than at the start of the rainy season.

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

Although much less effective than mulching at a rate of 2 t ha^{-1}, ridging may constitute an alternative for reducing soil losses by wind erosion on sandy soils. This will, however, require that ridges be closely spaced. The rapid collapse of conventional ridges following rainfall severely restricts their effectiveness at reducing soil fluxes, but the burial of millet stover in ridges may help stabilize ridges against the erosive action of wind and water. On somewhat finer textured soils ridges may be more stable and therefore become more effective for wind erosion control. However, such soils also become prone to surface crusting, with increased risk of runoff and erosion. Under such circumstances, the orientation of ridges with respect to the slope or the direction of the most erosive winds must be carefully weighted against the risk associated with wind or water erosion.

Vegètative barriers

Banzhaf *et al.* (1992) and Leinher *et al.* (1993) reported on the effectiveness of 5 m wide vegetative barriers made up of natural Savannah vegetation: annual grasses approximately 0.6 m high interspersed with scattered *Guiera senegalensis* bushes and the 2.5 to 3 m high perennial grass *Andropogon gayanus*. Compared to plots with vegetative barriers spaced 90 m apart, soil fluxes midway between windbreaks were reduced by 70% with 6 m spacing and by 53% for 20 m vegetative barriers spacing (Banzhaf *et al.*, 1992). Wind speed itself was reduced by more than 20% up to 10 m from the windbreak, i.e., up to 17 times the height of the herbaceous vegetation. No significant effect of the vegetative barriers on final millet yield in any of the three years of the experiment could be measured, irrespective of barrier spacing. Besides the protection it provides on the leeward side, natural fallow vegetation has been found to efficiently trap eroded saltating sediment. Bielders *et al.* (2002) reported an exponential decline in the windblown sediment mass flux as sediment was blown from a cultivated field into a natural vegetated fallow. Eighty-nine per cent of the incoming sediment for sand fluxes up to 57 kg m^{-1} could be trapped within the first 20 m of vegetated fallow land composed predominantly of herbaceous vegetation with scattered bushes (Fig. 6).

Michels *et al.* (1998) tested the impact of 5 windbreak species on millet yields and sediment fluxes during a three-year study. Sand fluxes were measured only in plots with *Andropogon gayanus* and *Bauhinia rufescens* windbreaks. All species were pruned to a height of 2 m and planted

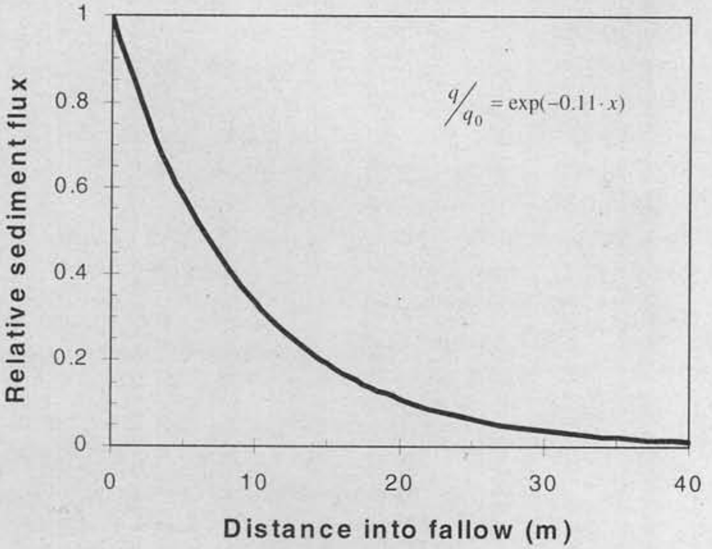

Fig. 6. Change in relative sediment flux (q/q_0) with distance (x) into a vegetated fallow for incoming fluxes (q_0) greater than 10 kg m^{-1} (after Bielders et al., 2002)

in double rows. Windbreak spacing was 30 m. Sand fluxes were reduced by 25% and 58% over the two years for *A. gayanus* and *B. rufescens* windbreaks, respectively. A significant reduction in sand fluxes was measured over distances up to 7 times the windbreak height for *B. rufescens*. In the case of the perennial grass *A. gayanus* windbreaks this effect extended for distances up to 5 times the height. Brenner *et al.* (1995) found that, in order to compensate for the loss of land allocated to the windbreak and the reduced yields close to the windbreaks as a result of competition, the optimal windbreak spacing would be of the order of 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.

For the three years of study the windbreak species did not have any effect on the number of hills buried under deposited sand, nor did Michels *et al.* (1998) detect any effect of the distance from the windbreak on this factor. The authors argued that this may have been due to the fact that wind erosion was not a serious constraint in those years. No consistent effect of windbreak on millet yields was observed over the three years. Some species tended to stimulate crop growth, whereas others depressed yields. Millet yields 1 to 3 m away from the windbreak were depressed by all species except *Faidherbia albida*, a leafless tree during the rainy season.

In accordance with the results of Banzhaf *et al.* (1992) and Leihner *et al.* (1993) the results of the studies of Michels *et al.* (1998)

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. From the point of view of millet production, *F. albida* windbreaks were by far the most effective in increasing yields, 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 improving soil fertility.

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 Vandenbeldt (1990) in a 4-year study. Ten meter wide strips of planted *A. gayanus* were alternated with equally wide strips of millet. No data on sand fluxes were collected, but the authors measured a 15 to 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 unprotected plots. Except in the first year, millet grain yields in protected plots tended to be depressed compared to unprotected plots. This may have been caused to some extent by competition for water for which Renard and Vandenbeldt (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 amounts 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.

Farmer's perspective on wind erosion control technologies

Several surveys at the village or household level have clearly revealed that farmers do not remain passive in the face of this land degradation process, but take active measures to control it within the limits of resources available to them (Baidu-Forson and Napier, 1998; Bielders *et al.*, 2001a; Lamers *et al.*, 1995; Sterk and Haigis, 1998). Sterk and Haigis (1998) reported that one or more wind erosion control techniques are implemented by 92% of the farmers they surveyed., Table 2 summarizes the various technologies used by farmers for wind erosion control in Niger.

In the absence of sufficient cover materials for mulching, farmers know that the topsoil layer becomes prone to wind erosion (Feil and Lamers, 1996). After several years, the end stage of the wind erosion process is a depression with a surface crust. For the different degradation stages Nigerian farmers even have special names in their own language (Lamers and Feil, 1995). Thus, Nigerian farmers are well aware that a soil cover is most effective to prevent wind erosion. Yet, a major disadvantage of any mulching technique is the need to apply it annually (Buerkert, 1995; Lamers, 1995). The acceptance by farmers of a broadcast mulch at a rate necessary to cover the soil adequately may be hindered by low production levels, additional labor demands,

Table 2. Wind erosion control techniques used by farmers and their additional advantages

Management techniques	Additional advantage/reason	Selected references
Vegetation barriers such as *Andropogon gayanus*	• Marks field borders • Provides construction material	Bielders *et al.*, 2001a; Raulin, 1965; Renard and Vandenbeldt, 1990
Management of natural vegetation with selected tree species such as *Combretum glutinosum*, *Piliostigma reticulatum*, *Guiera senegalensis*, and *Annona senegalensis*	• Provides food, feed, fire wood, medicinal products, • Improves soil fertility • Provides shade	Bielders *et al.*, 2001a; Feil *et al.*, 1995; Sterk and Haigis, 1998
Covering surface crusted spots with millet stalks, twigs from trees and shrubs, household refuse or any other mulching material	• Recover the soil • Increase soil fertility • High marginal net returns	Baidu-Forson and Napier, 1998; Bielders *et al.*, 2001a; Bielders *et al.*, 2000; Chase and Boudouresque, 1987; Lamers and Feil, 1995; Michels *et al.*, 1995b; Sterk and Haigis, 1998
Establishment of zays (planted pit-holes), half-moons or earth and rock bunds	• Increase of soil fertility • High marginal net returns	Scoones *et al.*, 1996; Sterk and Haigis, 1998; Vlaar, 1992
Leaving millet straw in the field	• Feed for livestock • Increase soil fertility	Baidu-Forson and Napier, 1998; Bielders *et al.*, 2001a
Manure application (promotes biomass development)	• Increase soil fertility	Bielders *et al.*, 2001a; de Rouw *et al.*, 1998; Sterk and Haigis, 1998
Partial second weeding (weeding only those parts of the field that are likely to yield grain)	• Reduction in labor	Bielders *et al.*, 2001a
Dead or live fencing (only on garden plots)	• Food or feed from live fences	Baidu-Forson and Napier, 1998; Bielders *et al.*, 2001a
Delayed weeding to ensure better ground cover during early millet growth		Bielders *et al.*, 2001a

particularly for planting, cutting and distributing, and by the profitability of alternative mulch uses.

The primary purpose of the techniques applied by farmers may not always be wind erosion control *per se*. Farmers prefer multipurpose management strategies with the principal aim to maintain soil fertility, rather than a strategy to prevent wind erosion only (Feil and Lamers, 1996; Lamers *et al.*, 1998;

Bielders *et al.*, 2001a). Indeed, soil conservation measures are rarely implemented spontaneously by farmers unless they provide short-term benefits in terms of crop production or for household consumption. For example, the perennial grass *Andropogon gayanus* is used to mark borderlines between fields and, at the same time, functions as a windbreak (Lamers *et al.*, 1996). Some farmers manage the natural regeneration of scattered tree vegetation, which helps not only to reduce wind erosion but it provides necessary food, feed and wood as well (Feil and Lamers, 1996). Particular tree species such as *Combretum glutinosum*, *Piliostigma reticulatum*, *Guiera senegalensis*, and *Annona senegalensis* are known to be effective against wind erosion and to catch eolian material, which improves soil fertility concurrently. In contrast farmers observe increased wind erosion underneath other tree species, which are tolerated nevertheless because they produce palatable and nutritive fruits and leaves (Feil and Lamers, 1996).

According to farmers, wind erosion is in fact promoted by an absence of biomass, and this is caused by low soil fertility and/or low rainfall. Since the latter is out of their reach, farmers focus efforts on soil fertility management. To maintain soil fertility, farmers in many Sahelian countries use techniques such as mulching, cover cropping, incorporation of organic matter, the use of animal manure, crop rotation, and leguminous crops as well as herding strategies (Hailu and Runtge-Metzger, 1992; Vlaar, 1992). Although these practices are not effective in establishing sustainable agro-ecosystems on a large scale (Hailu and Runtge-Metzger, 1992), it does show farmers' awareness of problems and possible solutions. Farmers cannot implement soil fertility and wind erosion control techniques on large scale applications due to insufficient resources and socio-economic and institutional constraints such as cattle ownership, land tenure, labor requirements, and input/output price relations.

Obviously farmers' efforts to prevent and restore wind erosion damages are based on the limited resources available (Lamers *et al.*, 1994). Hard surface crusts which often are the end result of wind erosion can be tilled with hoes as shown by research. However, farmers apply a less labor intensive and expensive methods. Farmers restore crusted spots by transferring millet stalks from more productive sites (Lamers and Feil, 1995), twigs from trees and shrubs, household refuse or any other mulching material (Lamers *et al.*, 1995), to such patches. After a period of 1-2 years, sediment trapping by the mulch leads to the development of a sandy topsoil, and the soil structure and soil fertility are improved following the decomposition of the organic material by termites (Chase and Boudouresque, 1987). Geiger and Manu (1993) concluded that the management of micro-sites should be adapted to their production potentials.

Other soil conservation practices in Niger and Burkina Faso, such as the use of zays (planted pit-holes enriched in manure or other forms of organic material), half-moons or earth and rock bunds, are based on traditional knowledge as well (Scoones *et al.*, 1996; Vlaar, 1992). These technologies are implemented on degraded (laterite) soils. Most preferred is the use of zays in combination with manure or P fertilizers, which ensures a short-term improvement, in combination with stone bunds for long term effects.

Only a technology that fits best the farming system will be adopted. Past evidence showed that these needed to be simple, inexpensive, based on local practices, and demanded few external inputs (Baidu-Forson and Ibro, 1995; Lamers and Feil, 1995). They produced short-term benefits and required a minimum of community organization. In contrast the economic feasibility of several soil conservation technologies examined in the past years is not ensured (Lamers and Bruentrup, 1996; Vlaar, 1992). These authors have shown that when recommending solely soil conservation techniques, they by themselves do not sustain productivity. Maximum benefits will be gained in case the soil conservation techniques are supplemented with additional inputs such as plant nutrients (Lamers, 1995; Vlaar, 1992). These additional costs come on top of the initial investments farmers need to pay and this reduces the chances for adoption.

In the past three decades much resources have been made available for research and developing specific innovations. Reports show that much emphasis is laid on design and implementation procedures, as well as on monitoring, maintenance and evaluation (Scoones *et al.*, 1996; Vlaar, 1992). Yet, one cannot focus on soil loss as the sole issue in the complex survival-oriented livelihood systems in the Sahel. Aside from wind erosion, farmers and households have concurrently to cope with short growing seasons, low inherent soil fertility, particularly phosphorus, limited and erratic rainfall, deep groundwater levels, and frequent droughts. Thus, developing a standardized technology for a single component of a complex cropping system without affecting other components is virtually impossible. Knowledge on the economic and social impact need to complement the knowledge of a decrease in soil loss.

Conclusions and Future Perspectives

Wind erosion constitutes a growing threat for the sustainable use of land resources in the Sahel. At present, however, it is rarely the primary constraint for agricultural production from the point of view of Sahelian farmers. Action programs designed to address the problems of land degradation and desertification should, therefore, take care of other priority issues such as famine, poverty, soil fertility and pest control, besides seeking farmer participation in wind erosion control programs.

Farmers are aware that their local technologies are becoming increasingly inadequate. A number of techniques are currently available to reduce soil and nutrient losses and crop damage by windblown sediment. As a rule, however, soil conservation measures will rarely be implemented spontaneously by farmers unless they provide short-term benefits in terms of crop production or for household consumption.

Mulching at a rate of 2 t ha^{-1} has been found to be a very effective means of reducing wind erosion-related damage. This practice relies on local skills and knowledge and is currently implemented by farmers, albeit at a small scale. Its large scale application is constrained by crop residue availability and its alternative uses. Although mulching at a rate of 2 t ha^{-1} has been found to increase millet yields, it often does not boost crop growth enough to sustain the application of such quantities (Buerkert, 1995). Soil fertility improvement is, therefore, a prerequisite before mulching can be promoted at a larger scale.

The use of lower mulch quantities may be a more practical alternative because it also allows some stover to be used for other purposes such as livestock feeding, fuel, or construction. Present knowledge indicates that a mulch application rate of 1.5 t ha^{-1} may provide suitable soil protection against wind erosion. Lower rates appear ineffective or may even enhance soil losses during intense sandstorms as a result of increased air turbulence. Although research in other parts of the world has demonstrated that standing stubble may be more effective in reducing wind velocity than mulches (Lyles and Allison, 1976), no research has been carried out to that effect in the Sahel. Future research should, therefore, concentrate on defining optimal crop residue management strategies, taking into account the specificity of the Sahelian farming systems.

Ridging may constitute a potential alternative for wind erosion control where mulching is constrained by the availability of crop residue. However, its widespread use on the sandy Arenosols will require solving a number of key issues, including labor and draught power requirements, availability of adequate tools, limited life span of ridges on sandy soils, and the detrimental effects of delayed sowing on millet yields. Burial of crop residue in ridges at the end of the cropping season may provide a partial answer to some of these issues.

Windbreaks appear suitable for reducing wind erosion but their large-scale implementation will require financial and institutional support as this technique is usually beyond the financial means, skills and knowledge of local farmers. In addition, the loss of land due to the windbreak and competition with the crops may require windbreak spacings that would provide inadequate soil protection. Nevertheless, windbreaks can provide short-term benefits in the form of wood, fruit, medicinal products, or fodder and may therefore constitute an attractive alternative for wind erosion control.

Natural fallow land is effective at reducing the long-range transport of windblown saltating sediment. As long as sufficient fallow land is present, wind erosion remains essentially a local land degradation process restricted to individual cultivated fields. With increasing population density and the gradual disappearance of fallow land, the risk of large scale land degradation by wind erosion becomes increasingly high. This may have severe implications for the future, in terms of land quality, the risk associated with agricultural production and human health.

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