Wind Erosion Processes and Control Techniques in the Sahelian Zone of Niger

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INTRODUCTION

The Sahelian zone of Africa drew world attention during the 17 years of drought that started in 1968. Some 25 million people faced famine as well as social and economic disruption. The long period of drought was even more tragic as the Sahel, already one of the world's poorest regions, is also the most subjected to desertification (Valentin, 1995). The tragedy painfully highlighted the urgent need to investigate causes and consequences of drought in the Sahel.

The term "Sahel" is derived from the Arabic word *Sahil* which means a coast or border (Hillel, 1991). The region can be seen as the transition zone between the arid Sahara in the north and the more humid Sudan zone in the south. It covers significant portions of Senegal, Mauritania, Mali, Burkina Faso, Niger, Chad, Sudan, and Eritrea. The limits correspond roughly with a mean annual rainfall of 200 mm in the north and 600 mm in the south (Le Houerou and Popov, 1981).

About 90% of the Sahelian population is rural, depending largely on subsistence agriculture (Sivakumar, 1989). The agricultural environment is characterized by soils that generally have sandy to sandy loam textures, low organic matter contents, and low native fertility, with phosphorus being the most limiting nutrient for crop growth (Manu et al., 1991). The soils are structurally unstable, prone to crusting and hardsetting (Valentin, 1995), and have low water holding capacities (Payne et al., 1990). In addition, climatic conditions are harsh, with highly variable rainfall during a short (3 - 4 months) rainy season, high temperatures, and potential evapotranspiration exceeding precipitation for most of the year. This combination of poor soils and harsh climatic conditions makes crop production difficult.

The sedentary farming systems combine free-roaming livestock with rainfed crop production. Most farmers possess sheep, goats, and often cattle, for milk and meat. The main crop is pearl millet (*Pennisetum glaucum*), which is often intercropped with cowpea (*Vigna unguiculata*). Millet is sown with the first rains in the rainy season. In intercropping systems the second crop is not sown until 2 to 3 weeks after the millet (Spencer and Sivakumar, 1987). More favorable micro-environments, with better moisture and nutrient conditions are used for sorghum (*Sorghum bicolor*), maize (*Zea mays*), sorrel (*Hibiscus sabdarifa*), okra (*Hibiscus esculentus*), and peanuts (*Arachis hypogaea*) (Taylor-Powell, 1991).

Continuous cropping causes soil organic matter and plant-available nutrients to decline. To restore soil fertility, farmers traditionally kept land under bush fallow for periods of 10 to 20 years. However, rapid population growth, at annual rates of about 3% during recent decades, has increased demand for food. Instead of intensifying farming systems, for instance by using mineral fertilizers, farmers have tried to enhance production by expanding the cropped area. The previously sustainable fallow system has broken down, yields have declined, and more marginal land, which used to be communal grazing land, is now cropped (Broekhuyse and Allen, 1988). Consequently, over-exploitation has resulted in land degradation, or desertification, on a large scale (Hillel, 1991). Land degradation implies a reduction of resource potential by a single process or a combination of processes acting on the land. These processes include erosion by water and wind, crusting and hard setting of soils, salinization and alkalinization, and long term reduction in the amount or diversity of natural vegetation (Dregne et al., 1991; Valentin, 1995).

The objective of this paper is to present a concise review of causes and consequences of wind erosion processes in Sahelian Africa. It includes the main results and conclusions of three years of field research in southwest Niger (Sterk, 1997). In particular, the relation between wind erosion and soil degradation is emphasized, and the possibilities for wind erosion control are discussed.

WIND EROSION

Wind erosion can become a problem whenever the soil is loose, dry, bare or nearly bare, and the wind velocity exceeds the threshold velocity for initiation of soil particle movement (Fryrear and Skidmore, 1985). In Niger, agricultural land is liable to wind erosion. Except for a few months in the growing season, soil surfaces are mostly bare and without adequate wind erosion control measures. Moreover, the sandy textures and dry climatic conditions make soils highly erodible for most of the year.

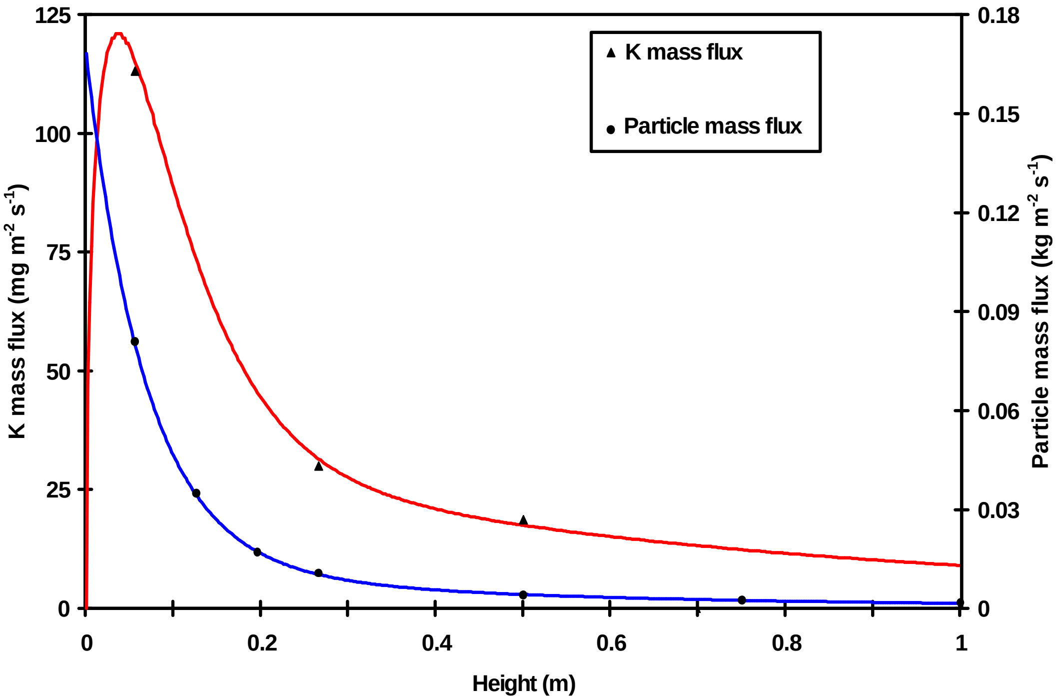
Winds that exceed the threshold wind speed for soil particle movement may occur during two distinct seasons. During the dry season (October - April), the area is subject to dry and rather strong northeastern winds, locally known as *Harmattan*, that may result in moderate transport (Michels et al., 1995a). The Harmattan winds originate over the Saharan desert, and from January to March they usually carry much dust from remote sources.

The second and most important erosion period is the early rainy season (May - July), when rainfall comes with heavy thunderstorms that move westward through the Sahel. Within a fully developed thunderstorm, strong vertical down drafts occur that cause a forward outflow of cold air which creates the typical dust storms of the Sahel. The duration of these events is usually short, approximately 10 to 30 minutes, but may result in intense soil particle movement (Michels et al., 1995a).

Seedlings sown after the first rains suffer from abrasion and burial in sand during these early rainy season storms. Abrasion, or sand blasting, damages plants by the scouring effect of blowing sand particles. Burial of plants causes problems after storms by reduced sunlight interception and by high soil temperatures during daytime. The damage ranges from reduced growth and development, and in the worst cases to total destruction of the crop (Michels et al., 1995b; Sterk and Haigis, 1998).

Wind-blown particle mass transport rates are characterized by a large spatial variation (Wilson and Cooke, 1980). For quantification of mass transport, Modified Wilson and Cooke (MWAC) sediment catchers (Sterk and Raats, 1996) were used during field experiments in southwest Niger. This type of catcher traps a mixture of saltation and suspension material at seven heights between 0.05 and 1.00 m. The overall trapping efficiency of the MWAC catcher for the sandy Sahelian soil is 0.49, which was determined in a wind tunnel (Sterk, 1993).

For each catcher and storm, a model was fitted through the seven observations to describe a vertical mass flux profile (Fig. 1). Integrating the profile to a height of 1 m and correcting for the trapping efficiency of the catcher resulted in a total mass transport value at the point of sampling. This value is equal to the mass of material moving below 1 m height that passed a strip 1 m wide



during the storm (Sterk and Raats, 1996).

At the start of the 1993 rainy season, 21 MWAC catchers were installed in an experimental plot of 40 by 60 m. Only four storms were sampled (Table 1), which was the total for the season. Storm based maps of wind-blown mass transport were produced by applying geostatistics (Sterk and Stein, 1997). Maps produced by kriging (which is a spatial interpolation technique) provided

Fig. 1. Example of vertical profiles fitted through particle mass fluxes and potassium (K) mass fluxes measured with a sediment catcher in southwest Niger, 13 June 1993.

Table 1. Descriptive statistics of four storms in southwest Niger, 1993 rainy season.

Date	Duration	Wind speed†	Wind direction	Mass transport‡	Soil loss§
	s	m s^{-1}		kg m^{-1}	Mg ha^{-1}
13 June	1481	10.3	SE	102.7	12.5
27 June	1320	7.6	S	15.5	2.0
30 June	1321	8.9	SE	31.8	4.6
1 July	3004	9.2	SSE	149.8	26.8

† Mean wind speed measured at 2 m.
‡ Average value of 21 total mass transport values.
§ For calculation procedure see Sterk and Stein (1997).

the best linear unbiased predictions of mass transport at every unsampled location (Fig. 2). These maps were used to calculate sediment balances for the plot, and to determine storm based soil losses (Table 1). The calculated loss from the plot during the four storms was 45.9 Mg ha^{-1}, which corresponds to a soil layer with an average depth of 2.7 mm.

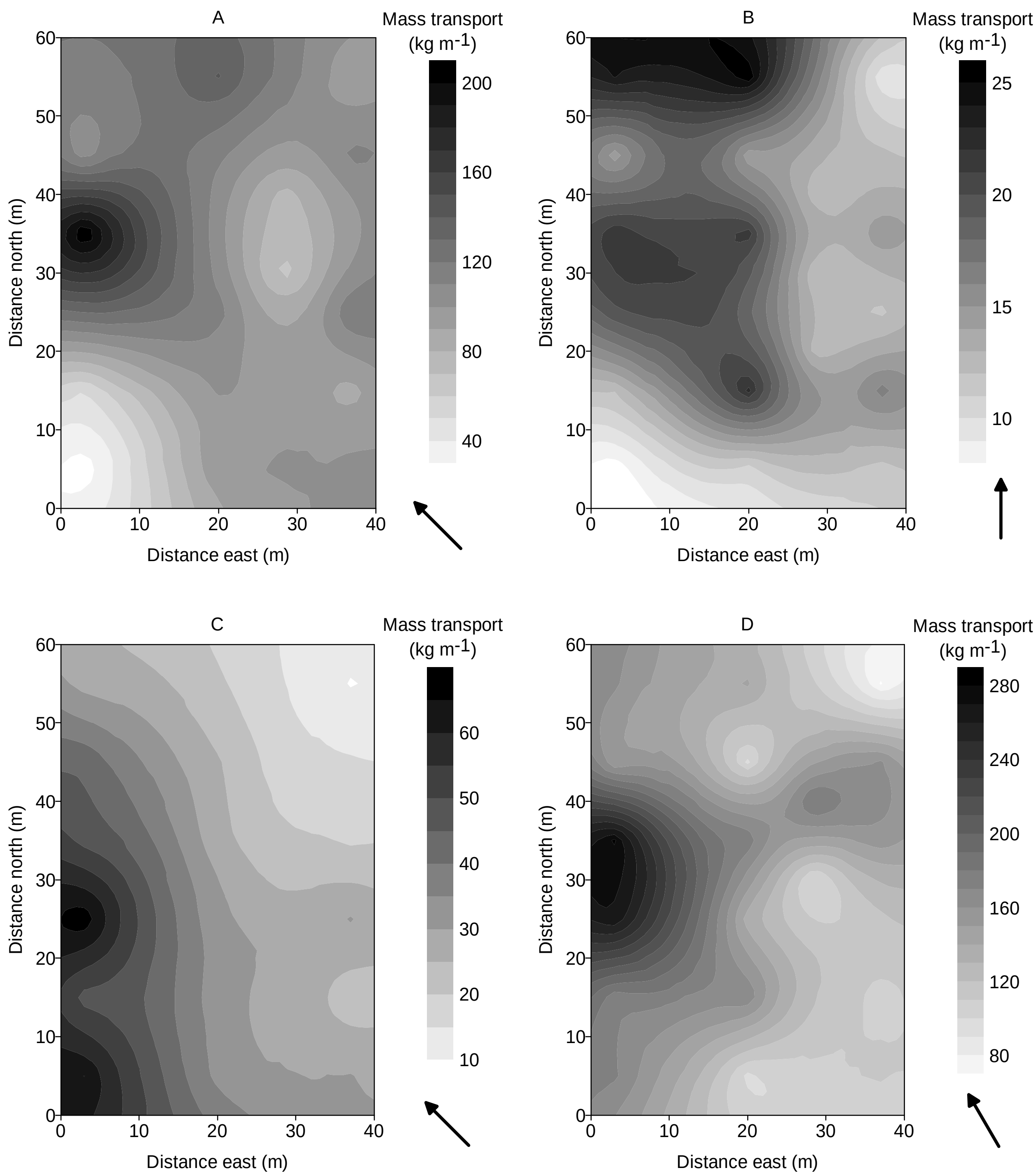


Fig. 2. Interpolated maps of total mass transport (kg m^{-1}) in an experimental plot in southwest Niger. Storm dates are (A) 13 June, (B) 27 June, (C) 30 June, and (D) 1 July 1993. Arrows indicate the direction of the average wind speed vector.

Soil particle losses are not the main concern for Nigerien farmers. Of more importance are the nutrients that are lost from the low fertility soils with wind-eroded material. Estimates of nutrient losses were made only for the first and the fourth storm of the 1993 rainy season (Sterk et al., 1996). The second and third storm were too small to have sufficient material trapped for nutrient analyses. During both storms, samples were collected from 18 catchers at heights of 0 (= topsoil), 0.05, 0.26, and 0.50 m. The samples were analyzed on total element (TE) contents of potassium (K), carbon (C), nitrogen (N), and phosphorus (P). The average enrichment ratios, which are the ratios of TE content in the sediment to the TE content in the topsoil are presented in Table 2. In general, nutrient contents increased with height owing to a relative increase in clay and silt particles that contain disproportionately greater amounts of nutrients than the coarser sand moving at lower heights (Young et al., 1985). But, combining the TE contents with the particle mass flux profiles shows that the main mass of nutrients was transported just above the soil surface where saltation is dominant (Fig. 1). This can be explained by the presence of aggregates that contain fine particles (clay + silt) and are transported by saltation (Zobeck and Fryrear, 1986). Hence, part of the nutrients in the fine fraction are also transported by saltation. Integration of the TE mass flux profiles over height and correction for the trapping efficiency of the catchers resulted in total TE mass transport rates. These were used to estimate nutrient losses from the plot by calculating mass balances for each element. The total losses were 57.1 kg K ha^{-1}, 79.6 kg C ha^{-1}, 18.3 kg N ha^{-1}, and 6.1 kg P ha^{-1}, which corresponds to approximately 3% of the TE masses that were present in the top 0.10 m of the soil (Sterk et al., 1996).

Saltation and suspension transport have different impacts on soil productivity. Saltation transports material over limited distances, from unprotected sources towards protected sinks. For instance, a fallow site with adequate vegetation cover traps saltation material coming from surrounding source areas, like millet fields. So, the fertility status of the fallow site is improved at the expense of decreasing soil productivity in upwind areas. This process occurs also on a smaller scale. Individual shrubs trap wind-blown material from nearby sources. The resulting

Table 2. Average enrichment ratios of a dust sample and trapped erosion materials for two storms at ICRISAT Sahelian Center, 1993 rainy season.

		Enrichment ratio†			
	Height	K	C	N	P
	m				
13 June	0.05	1.18	1.33	0.83	0.98
	0.26	1.91	2.39	1.42	1.10
	0.50	2.06	3.02	2.08	1.14
1 July	0.05	1.27	1.47	0.83	0.91
	0.26	2.58	2.63	1.33	1.40
	0.50	4.15	4.74	2.25	1.98

† Ratio of the total element content of trapped sediment to the total element content of the topsoil.

micro dunes formed by wind deposits are known to farmers as having the best productivity after the shrubs have been cut down (Sterk et al., 1996; Sterk and Haigis, 1998). However, reduced runoff and soil enrichment by the shrub itself are also important factors that contribute to a better soil productivity.

Suspended dust raised from a field by a convective storm may be carried over long distances, resulting in a loss of fine particles and nutrients and thus enhancing regional soil degradation. Several observations of dust from West Africa crossing the Atlantic were reported in the literature (e.g., Prospero et al., 1970; Carlson and Prospero, 1972; Westphal et al., 1988). Prospero and Carlson (1972) estimated that between 25 million and 37 million Mg of wind-blown dust cross the Atlantic annually, with even greater amounts presumably deposited in the ocean (Lal, 1988). Apart from losses, the Sahel also receives nutrient-rich dust deposits. During the Harmattan season, dust is transported from the Sahara towards the Sahel, where it partly settles. Moreover, during the early rainy season, some of the dust raised by a convective storm is deposited by gravity or rain wash-out. Drees et al. (1993) measured 50% of the total annual dust input in southwest Niger in the early rainy season, whereas the Harmattan season contributed only 15% to the total. Dust deposits are particularly rich in sodium, potassium, magnesium, and calcium, but poor in phosphorus (Herrmann et al., 1996).

The balance between input and output of dust remains uncertain due to a lack of reliable data. Soil surfaces that are well protected by vegetation or soil conservation measures can only benefit from dust deposits. On the other hand, uncovered land is more susceptible to losses than to inputs of dust. Since large areas in Niger are bare and unprotected nowadays, it is likely that suspension transport results in a net loss of soil particles and nutrients.

WIND EROSION CONTROL

The negative impact of wind erosion on cropping systems can be prevented by applying wind erosion control measures. Successful applications of technical measures like raising wind breaks, strip cropping, and mulching were reported from the US (e.g., Tibke, 1988). However, much less is known about adoption of these methods by Sahelian farmers.

Interviews held with 138 farmers from seven villages in southern Niger (Sterk and Haigis, 1998) revealed that 81% of the farmers consider wind erosion a problem for their crop production systems. Most farmers (96%) know techniques to reduce wind erosion, and 92% applied one or more of those techniques in the field during the 1995 rainy season. The indigenous wind erosion control measures are mulching with crop residues or tree branches, and application of manure. In two of the seven villages new control techniques have been introduced by an agricultural development project. These techniques include tree planting, regeneration of natural woody vegetation, and *zaï*, a method of soil preparation using pits filled with compost. None of the farmers mentioned strip cropping or wind breaks as a means to reduce erosion.

Application of manure and *zaï* are not real wind erosion control measures but rather are cultural practices to improve soil fertility. Fertilization results in better growth and development of crops, making plants more resistant against damage caused by sand transport. Moreover, biomass production will be greater, creating better soil protection, and more mulch material will be available after harvest. But, the fertilization techniques are also limited by insufficient availability of manure and compost (Lamers and Feil, 1995).

Mulching is the most widely applied control technique in the Sahelian zone of Niger, but is limited by scarce availability of tree branches and crop residues. Millet residue is by far the most commonly used mulch material, but is also needed for other purposes like fuel, fodder, and construction. In a previous study it was shown that covering the soil with 2000 kg ha^{-1} of millet residues gives sufficient protection, whereas a mulch cover of 500 kg ha^{-1} does not reduce sediment transport (Michels et al., 1995a). With an average biomass production of 2200 kg ha^{-1} (Manu et al., 1991) and the high demand for other purposes, it is unrealistic to expect that farmers can leave 2000 kg ha^{-1} of millet residue in the field. Therefore, two intermediate quantities of millet residue were tested for their efficacy in reducing sediment transport.

A field experiment was conducted in southwest Niger during the 1994 and 1995 rainy seasons (Sterk and Spaan, 1997). Within a pearl millet field, two plots of 55 by 70 m were selected and equipped with 10 MWAC sediment catchers. In both seasons, the plots were left bare during the first three weeks of the experiment, and afterwards one plot was covered with flat millet stalks (randomly distributed). Applied quantities were 1500 kg ha^{-1} in 1994, and 1000 kg ha^{-1} in 1995, corresponding to estimated soil covers of 7.1 and 4.7%, respectively. Twenty storms were sampled during the two seasons.

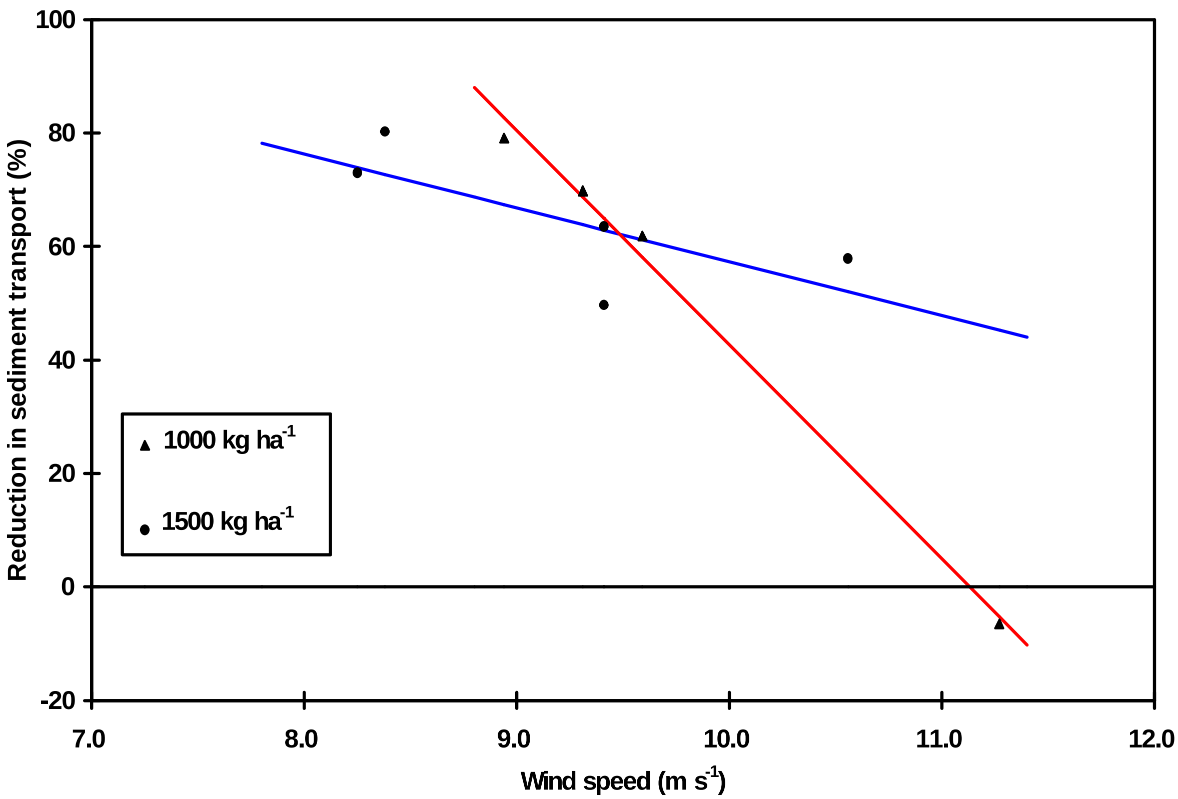


Fig. 3. Relationship between average wind speed of a storm and the reduction in sediment transport caused by mulch covers of 1500 kg ha^{-1} and 1000 kg ha^{-1} of flat pearl millet stalks.

To determine the effect of millet residue on sediment transport, the difference in average total mass transport rates between the plots when bare was first quantified with a multiple linear regression model. This allowed to estimate the inherent differences in erodibility between the two plots, and hence, to quantify more accurately the specific effects of the mulches on sediment transport. On average, total mass transport rates were reduced by 63.6% with 1500 kg ha^{-1}, and by 42.2% with 1000 kg ha^{-1} of millet residue (Sterk and Spaan, 1997).

The efficiency of millet stover at reducing sediment transport decreases as wind speed increases (Fig. 3). The effect was stronger for the 1000 kg ha^{-1} mulch cover, which even enhanced sediment transport by 6.5% during one strong storm. This could be explained by increased turbulence caused by the roughness of the residues. The 1500 kg ha^{-1} mulch cover reduced sediment transport by at least 50% during all sampled storms, and is therefore recommended as the better application rate for wind erosion control in Niger. However, such a quantity is still more than what farmers usually have available for soil protection. Hence, there exists a need for control techniques that fit better into the farming systems.

Tree planting and stimulation of regeneration of natural woody vegetation are measures that have an influence on the wind field in a certain area. They are particularly effective when applied on a village scale or larger scales. Then, the trees and shrubs act as roughness elements and reduce wind speeds in the whole area. Furthermore, shrubs with dense canopies starting near the soil surface may trap wind-blown particles and protect the soil from erosion (Sterk et al., 1996). In addition, more trees and shrubs enhance the availability of mulch material in the area. According to the farmers that applied these measures, they are very successful in soil conservation and crop protection (Sterk and Haigis, 1998). Farmers from other villages also mentioned regeneration of natural vegetation as a possibility to reduce wind erosion. It is therefore recommended that future research on wind erosion control in Niger should concentrate on developing strategies to increase biomass production for mulching, and to stimulate regeneration of natural vegetation on farm and village scales.

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REFERENCES

Broekhuyse, J.T., and A.M. Allen. 1988. Farming systems research. Human Organiz. 47: 330-342.

Carlson, T.N., and J.M. Prospero. 1972. The large-scale movement of Saharan air outbreaks over the northern equatorial Atlantic. J. Appl. Meteorol. 11: 283-297.

Drees, L.R., A. Manu, and L.P. Wilding. 1993. Characteristics of aeolian dusts in Niger, West Africa. Geoderma 59: 213-233.

Dregne, H.E., M. Kassas, and B. Rosanov. 1991. A new assessment of the world status of desertification. Desertification Control Bull. 20: 6-18

Fryrear, D.W., and E.L. Skidmore. 1985. Methods for controlling wind erosion. p. 443-457. *In* R.F. Follet and B.A. Stewart (ed.) Soil erosion and crop productivity. ASA-CSSA-SSSA, Madison, WI.

Herrmann, L., K. Stahr, and M.V.K. Sivakumar. 1996. Dust deposition on soils of southwest Niger. p. 35-47. *In* B. Buerkert et al. (ed.) Wind erosion in West Africa: The problem and its control. Proc. Int. Symp., Stuttgart, Germany. 5-7 Dec. 1994. Margraf Verlag, Weikersheim, Germany.

Hillel, D.J. 1991. Out of the earth: Civilization and the life of the soil. The Free Press, New York.

Lal, R. 1988. Soil degradation and the future of agriculture in sub-Saharan Africa. J. Soil Water Conserv. 43: 444-451.

Lamers, J.P.A., and P.R. Feil. 1995. Farmers' knowledge and management of spatial soil and crop growth variability. Netherlands J. Agric. Sci. 43: 375-389.

Le Houerou, H.N., and G.F. Popov. 1981. An eco-climatic classification of intertropical Africa. FAO Plant Production and Protection Paper, no. 31. FAO, Rome, Italy.

Manu, A., A. Bationo, and S.C. Geiger. 1991. Fertility status of selected millet producing soils of West Africa. Soil Sci. 152: 315-320.

Michels, K., M.V.K. Sivakumar, and B.E. Allison. 1995a. Wind erosion control using crop residue I. Effects on soil flux and soil properties. Field Crops Res. 40: 101-110.

Michels, K., M.V.K. Sivakumar, and B.E. Allison. 1995b. Wind erosion control using crop residue II. Effects on millet establishment and yields. Field Crops Res. 40: 111-118.

Payne, W.A., C.W. Wendt, and R.J. Lascano. 1990. Root zone water balances of three low-input millet fields in Niger, West Africa. Agron. J. 82: 813-819.

Prospero, J., and T. Carlson. 1972. Vertical and aerial distribution of Saharan dust over the western equatorial North Atlantic Ocean. J. Geophys. Res. 77: 5225-5265.

Prospero, J.M., E. Bonatti, C. Schubert, and T.N. Carlson. 1970. Dust in the Caribbean atmosphere traced to an African dust storm. Earth Planetary Sci. Letters 9: 287-293.

Sivakumar, M.V.K. 1989. Agroclimatic aspects of rainfed agriculture in the Sudano-Sahelian zone. p. 17-38. *In* Soil, crop, and water management in the Sudano-Sahelian zone. Proc. Int. Worksh., Niamey, Niger. 11-16 Jan. 1987. ICRISAT, Patancheru, India.

Spencer, D.S.C., and M.V.K. Sivakumar. 1987. Pearl millet in African agriculture. p. 19-31. *In* Proceedings of the international pearl millet workshop. Patancheru, India. 7-11 April 1986. ICRISAT, Patancheru, India.

Sterk, G. 1993. Sahelian wind erosion research project, Report III. Description and calibration of sediment samplers. Erosion and Soil & Water Conservation Group, Wageningen Agric. Univ., Wageningen, The Netherlands.

Sterk, G. 1997. Wind erosion in the Sahelian zone of Niger: Processes, models, and control techniques. Thesis, Erosion and Soil & Water Conservation Group, Wageningen Agric. Univ., Wageningen, The Netherlands.

Sterk, G., and J. Haigis. 1998. Farmers' knowledge of wind erosion processes and control methods in Niger. Land Degradation Developm. (in press).

Sterk, G., and P.A.C. Raats. 1996. Comparison of models describing the vertical distribution of wind eroded sediment. Soil Sci. Soc. Am. J. 60: 1914-1919.

Sterk, G., and W.P. Spaan. 1997. Wind erosion control with crop residues in the Sahel. Soil Sci. Soc. Am. J. 61: 911-917.

Sterk, G., and A. Stein. 1997. Mapping wind-blown mass transport by modeling variability in space and time. Soil Sci. Soc. Am. J. 61: 232-239.

Sterk, G., L. Herrmann, and A. Bationo. 1996. Wind-blown nutrient transport and soil productivity changes in southwest Niger. Land Degradation Rehabil. 7: 325-335.

Taylor-Powell, E. 1991. Integrated management of agricultural watersheds: Land tenure and indigenous knowledge of soil and crop management. TropSoils Bulletin 91-04. Texas A&M Univ., College Station, TX.

Tibke, G. 1988. Basic principles of wind erosion control. Agric. Ecosyst. Environ. 22/23: 103-122.

Valentin, C. 1995. Sealing, crusting and hard setting soils in Sahelian agriculture. p. 53-76. *In* H.B. So et al. (ed.) Sealing, crusting and hard setting soils: Productivity and conservation. Australian Soc. of Soil Sci., Brisbane, Australia.

Westphal, D.L., O.B. Toon, and T.N. Carlson. 1988. A case study of mobilization and transport of Saharan dust. J. Atmos. Sci. 45: 2145-2175.

Wilson, S.J., and R.U. Cooke. 1980. Wind erosion. p. 217-251. *In* M.J. Kirkby and R.P.C. Morgan (ed.) Soil Erosion. John Wiley & Sons, Chichester, UK.

Young, R.A., A.E. Olness, C.K. Mutchler, and W.C. Moldenhauer. 1985. Chemical and physical enrichments of sediment from cropland. p. 107-116. *In* Erosion and Soil Productivity. ASAE Publication No. 8-85.

Zobeck, T.M., and D.W. Fryrear. 1986. Chemical and physical characteristics of windblown sediment I. Quantities and physical characteristics. Trans. ASAE 29: 1032-1036.