AGROCLIMATOLOGY AND MODELING

Soil Tillage and Windbreak Effects on Millet and Cowpea: I. Wind Speed, Evaporation, and Wind Erosion

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ABSTRACT

Deforestation, overgrazing, and declining soil regeneration periods have resulted in increased wind erosion problems in dry areas of the West African Sahel, but little is known about the bio-physical factors involved. This research was conducted to determine the effects of ridging and four different windbreak spacings on wind erosion, potential evaporation, and soil water reserves. A field trial was conducted from 1985 to 1987 on 12 ha of a Psammentic Paleustalf in Southern Niger. Millet, *Pennisetum glaucum* (L.), and cowpea, *Vigna unguiculata* (L.) Walp., were seeded in strips on flat and ridged soil. Windbreaks of savannah vegetation were spaced at 6, 20, 40, and 90 m. The effects of ridging on wind speed, evaporation, and wind erosion were small and mostly non-significant. However, average wind speed at 0.3 m above ground in the center of cowpea and millet strips was significantly reduced from 2.8 to 2.1 m s^{-1} as windbreak distances narrowed from 90 to 6 m. As a consequence, potential evaporation declined by 15% and the amount of wind blown soil particles by 50% in ridged and by 70% in flat treatments. Despite reduced potential evaporation, average subsoil water reserves were 14 mm smaller in the 6- than in the 20-m windbreak spacing indicating excessive water extraction by the windbreak vegetation. Thus, establishing windbreaks with natural savannah vegetation may require a careful consideration of the agronomic benefits and costs to competing crops.

DEFORESTATION, OVERGRAZING , and reduced fallow periods in the West African Sahel have increased wind erosion problems. Sandblasting or burying of crops are the consequences. Low overall rainfall, irregular rainfall distribution, soil crusting, and high soil temperatures provide additional climatic and soil-physical constraints to crop growth and yield (ICRISAT, 1986).

At early growth stages, crops can suffer severely from wind. Studies by Fryrear (1963) and Armburst (1984) have shown that physical damage to wheat leaves caused a twofold or greater increase in leaf conduct-

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ance. Macroscopic features of damage were even more evident when the wind carried particles of sand. It is widely assumed that wind increases crop transpiration at all growth stages, but this is contradicted by findings of Monteith (1965), Drake et al. (1970), and Dixon and Grace (1984) who have shown increased wind speed either has no effect or decreases transpiration of mature crops. For leaves exposed to high irradiance, as frequently occurs in the tropics and subtropics, an increase in wind speed actually may mean a decline in crop transpiration rate (Grace, 1977). Fully developed crops suffer less severely from the effect of air movement than young emerging plants. Therefore, protection from erosive and abrasive winds in a semi-arid environment may be needed most during early plant development. Wind speed close to the soil surface can be reduced by increasing surface roughness by ridging, for example (Fryrear, 1984). Furthermore, windbreaks consisting of naturally growing or planted vegetation belts are considered to be effective against the damaging action of wind (Hagen et al. 1972; Kreutz, 1952, p. 51–54)

International and national research institutions in the Sahel are still examining the effects of different types of planted windbreaks on crop performance. We report on the results of an experiment where naturally growing savannah vegetation was used as a low cost windbreak for millet and cowpea. This paper describes some of the changes in microclimatic and soil parameters caused by soil tillage and windbreak treatments. In a second paper (Leihner et al., 1993), the influence of these changes on crop growth and yield is examined.

MATERIALS AND METHODS

Climatic and Soil Conditions

Field research was conducted from 1985 to 1987 at the International Crops Research Institute for the Semi-Arid Tropics ICRISAT Sahelian Center (ISC) at Sadoré (13° 15'N, 2° 10'E), in Niger, West Africa. Average annual temperature at this location is 29 °C, with an average monthly maximum of 42 °C in April and an average monthly minimum of 14 °C in January. The 61-yr average annual rainfall is 574 mm distributed unimodally throughout the months June through October (West et al., 1984). During the experiment, total annual rainfall was 558 mm in 1985; 641 mm in 1986; and 363 mm in 1987. The soil at the research site is a Psammentic Paleustalf with 90% sand, 4% clay, a pH (H_2O) of 4.9, an organic C content of 2.5 g kg^{-1} and a CEC of 1.3 $cmol_c$ kg^{-1} in the upper 0 to 0.3 m (West et al., 1984, p. 32).

Experimental Design, Planting, and Fertilization

A field trial was established on a 12-ha area of natural bush savannah. The following three factors were arranged in a split-split plot design with three blocks as replications: (i) flat vs. ridged land preparation as mainplots (ii), windbreak distances of 6, 20, 40, and 90 m as the randomly assigned subplots, and (iii) millet and cowpea as the sub-subplots (Fig. 1). Block size was 392 by 95 m. The three replicates were arranged in a line along the eastern fence of the research station, perpendicular to the main wind direction blowing mostly from the East. Naturally growing fallow vegetation, 5 m wide, was left in place as windbreaks. Dominant annual species in the shelterbelts were *Cenchrus biflorus* Roxb. and *Cassia mimosoides* L. whereas the most frequent perennials were *Stylosanthes* spp., *Tephrosia* spp., *Guiera senegalensis* (J. Gmelin), and *Andropogon gayanus* Kunth. The annual species created a rather homogeneous obstacle of 0.6-m height. Guiera bushes and andropogon grass were randomly dispersed along the shelterbelts at an average distance of 5.6 m, reaching a height of 2.5 to 3 m. During the 3 yr of the experiment, additional afforestation was done in the shelterbelts by transplanting 8-mo-old seedlings of *Acacia albida* Del., *Acacia nilotica* (L.) Willd. ex Del. (var. adansonii), and *Bauhinia rufescens* (Lam.) at a distance of 2 m in the row and 1 m between rows. A circle, 0.5 m wide, was hand-weeded around the young trees once after planting but trees were not watered or fertilized. Trees measured around 0.3 m at planting and reached a height of 0.8 to 1.0 m during the experiment's 3-yr duration. Land preparation in the crop area between the windbreaks was done by disk-harrowing or ridging once after the first rainfall events totaled 20 mm in 3 d. Ridges were oriented perpendicular to the main wind direction. Spacing was 0.75 m and height 0.25 m with the furrow bottom 0.15 m below and the top of the ridge 0.10 m above the zero reference point.

Data Collection

Wind speed calculated from total wind run was measured with mobile cup anemometers (Mod. 1483; Lambrecht, Göttingen, Germany) 0.3 m above the bare soil on 5 d before millet planting. From 0700 to 1700 h, hourly readings were conducted in millet sub-subplots at five measuring points arranged in transects across cultivated strips (Fig.1). To compute the relative wind speed, a control measurement was taken 0.1 m above the savannah vegetation of the most upwind shelterbelt. Anemometers were installed at 0.3-m height halfway between windbreaks in each millet sub-subplot to record total wind run and calculate average wind speed from 10 d before to 20 d after crop emergence.

To determine potential evaporation, unprotected "Piché Evaporimeters" (Lambrecht, Germany) were set up at 0.3-m height in the center between windbreaks in sub-subplots close to the anemometers and readings were taken simultaneously with total wind run. Wind eroded soil was quantified with modified "Bagnold Sandcatchers" (dePloey and Gabriels, 1980, p. 63–96), which collected soil particles from 0.05 to 0.5 m above ground. In two of the three replications, a total of 16 sandcatchers was installed in the millet plots halfway between all windbreak distances on both ridged and flat soil surfaces. The amounts of soil collected in the center of the 90-m-spaced windbreaks were set on 100 and relative quantities from other spacings calculated as percentages of these control values. Soil temperature at 2-cm depth was measured weekly with a portable thermocouple (Testotherm, Germany) in the center of all plots in one replicate. Soil moisture was monitored periodically during the growing season in a three-point transect between the windbreaks (Fig.1) at depths of 0.35, 0.70, 1.80, and 2.40 m with a neutron probe (Troxler, Research Triangle Park, NC) and gravimetrically at a depth of 0 to 0.25 m.

Data Analysis

Data from the sub-subplot treatments were analyzed separately using a split-plot model. Standard analysis of variance was used to determine treatment effects on microclimatic parameters.

RESULTS

With flat land preparation, shelter belts reduced wind speed to 80% of the control up to 10 m leeward of

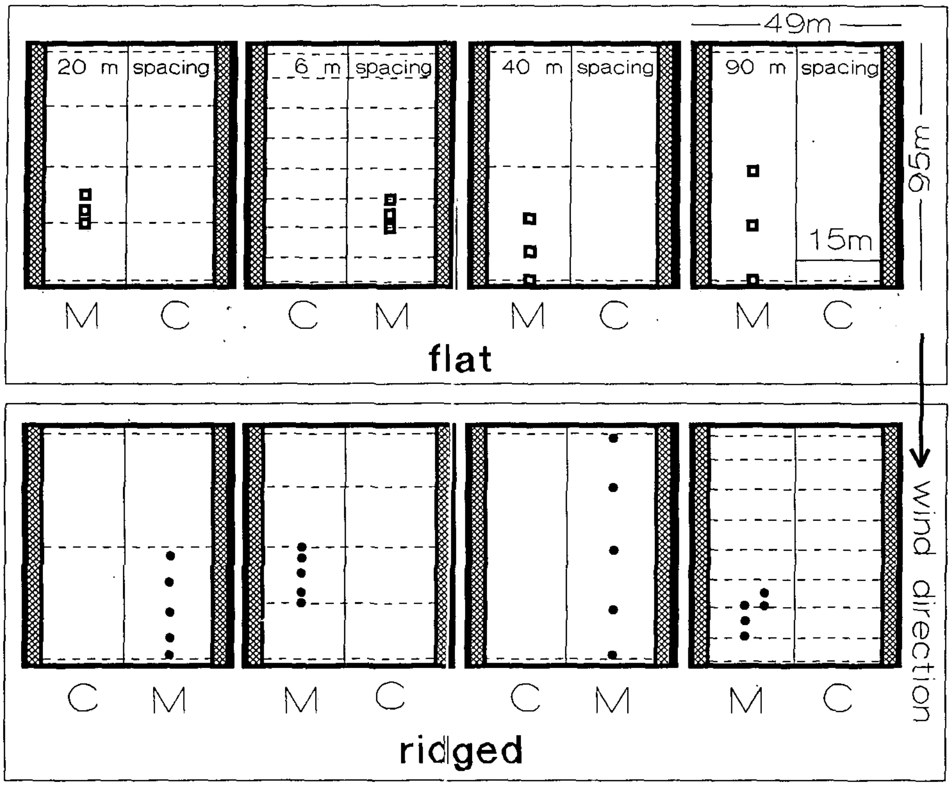

Fig. 1. Schematic diagram of field-layout (one replication). The crops were millet (M) and cowpea (C). Flat and ridged blocks were arranged side by side. Windbreaks (dotted lines) spaced 6, 20, 40, and 90 m were oriented north-south. Erosive winds came from the east. Symbols indicate locations where measurements of wind speed (●) and subsoil moisture (□) were taken in both flat and ridged treatments.

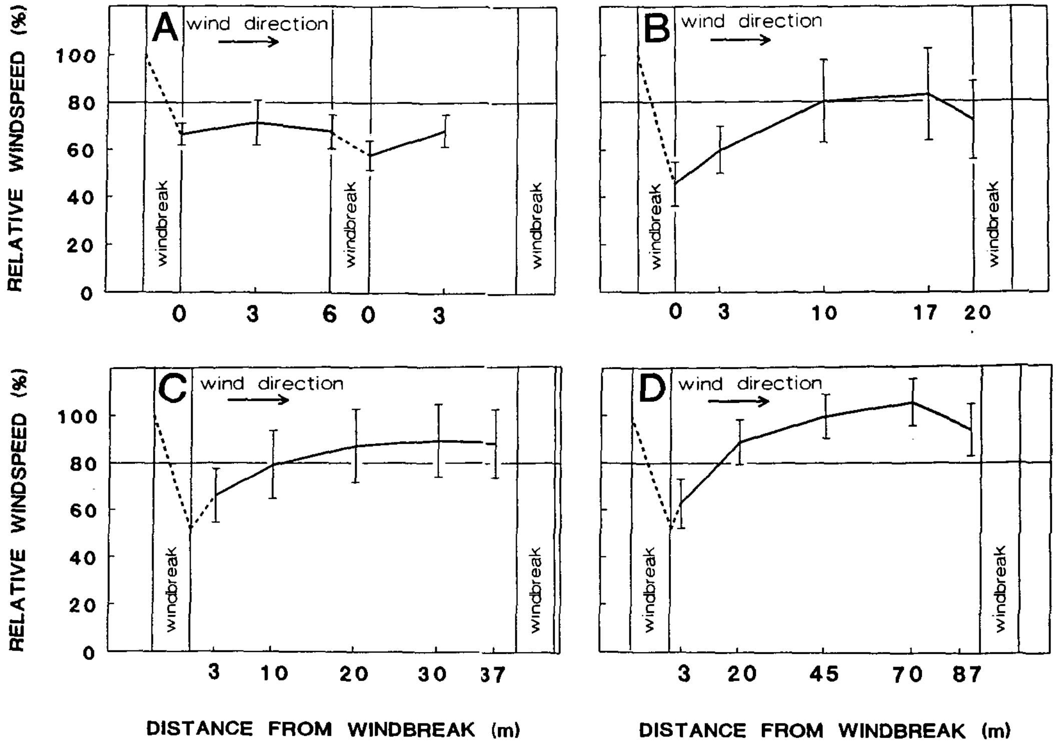

Fig. 2. Wind speed profiles for different windbreak distances: *A* - 6 m, *B* - 20 m, *C* - 40 m, *D* - 90 m. Data are means of repeated measurements taken at 0.3-m height above a flat bare soil surface. Bar intervals indicate one standard deviation.

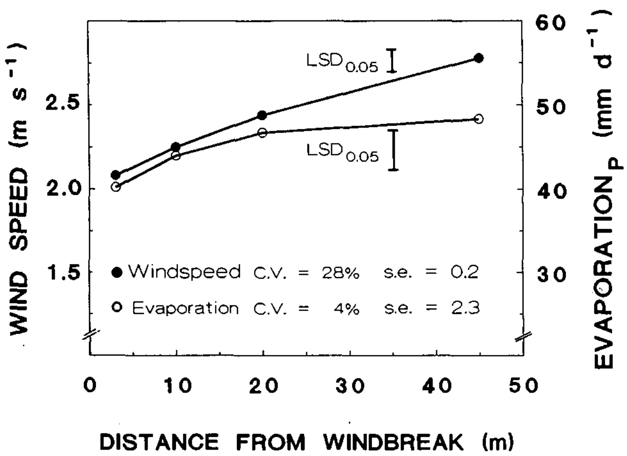

Fig. 3. Wind speed and Piché evaporimeter evaporation at different windbreak distances. Data points are averages of measurements at 0.3-m height in the center of ridged and flat plots before and during crop emergence.

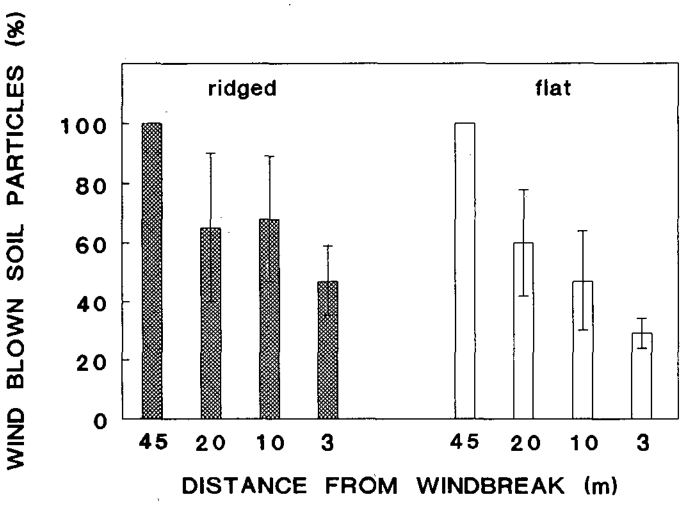

Fig. 4. Relative amount of wind blown soil particles caught at 0.05- to 0.5-m height in the center of the plots at different windbreak distances. Bar intervals indicate one standard deviation.

the windbreaks, which corresponds to 17 times the height of the annual shelter belt species (Fig. 2A-D). This area was defined as the area influenced by windbreaks (Blenk and Trienes, 1956). With ridges, the distance of wind speed reduction to 80% of the control varied between 3 and 17 m (data not shown). Neither wind speed nor evaporation measurements indicated a significant difference between ridged and flat soil preparation, thus data for both mainplot treatments were averaged. Average wind speed was significantly reduced as the distance from the measuring point to the windward windbreak decreased from 45 to 3 m; potential evaporation also decreased significantly (Fig. 3).

Another direct result of reduced wind speed was reduced airborne soil particles in 0.05- to 0.5-m height halfway between the shelter belts spaced 6 and 20 m apart compared to the 90-m spaced shelter belts (Fig.4). Chepil (1945) found in wind tunnel studies that 75% of all wind-eroded material in this layer moves in saltation. In flat plots at 3 m leeward from a windbreak, the amount of airborne soil particles was 30% of that measured at a distance of 45 m leeward from a windbreak. This gradient was less pronounced in ridged plots (Fig. 4).

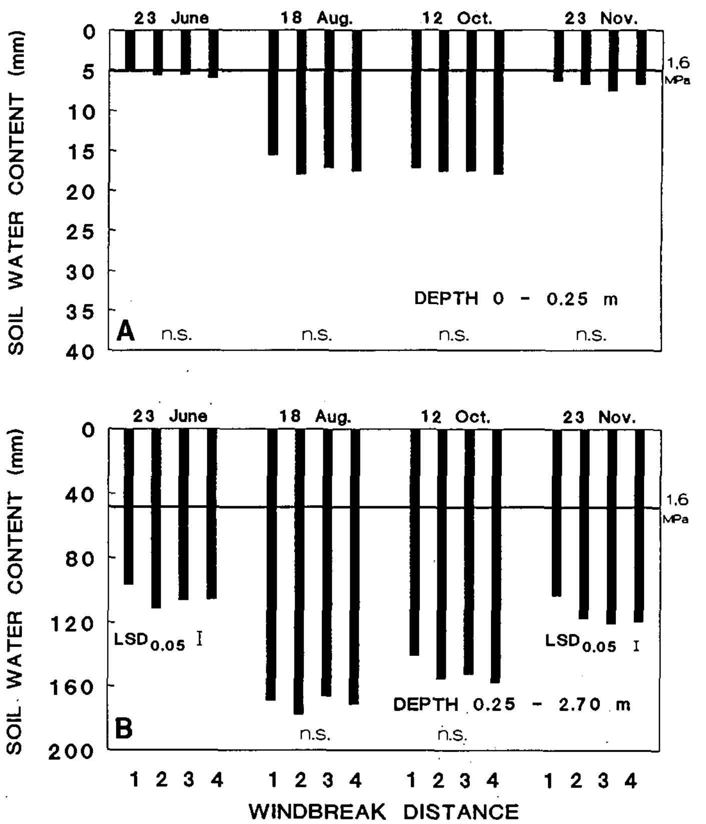

Fig. 5. Soil water content over time in 1987 for different windbreak distances (1 = 6 m, 2 = 20 m, 3 = 40 m, 4 = 90 m). For the depth 0 to 0.25 m (*A*) one measurement was taken. For the interval from 0.25 to 2.70 m (*B*) columns show averages of measurements taken at 0.35-, 0.70-, 1.80-, and 2.40-m depth. Lines across the columns represent the soil water content at the permanent wilting point (1.6 MPa).

For the 1987 growing period, soil water contents in the 0- to 0.25-m layer were similar in all subplots (Fig. 5A). In the 0.25- to 2.70-m layer, however, at the beginning as well as the end of the season, soil water contents were significantly lower between the 6-m spaced windbreaks than at other spacings. During the months with major rainfall events, no significant differences were observed as soil water reserves were fully replenished (Fig. 5B). Also, early and late in the 1987 growing season, subsoil water contents were up to 14 mm less at the windbreak-crop interface than those in the plot centers. With greater total rainfall and a more even rainfall distribution in the two previous seasons, no significant subsoil moisture differences were found at any of the observation dates and transect measurement points (data not shown).

During planting, soil temperatures at 0.02-m depth averaged 31 °C in moist soil on cloudy days and reached an average of 56 °C with dry soil on sunny days. No differential effects on soil temperature were detected due to land preparation or windbreak distance treatments.

DISCUSSION

The effects of soil tillage method and windbreaks on wind speed and eddy formation are universal phenomena with applicability in different climatic zones (Hagen, 1976; Wilson and Cook, 1980). Interacting variables are the windbreak's porosity, its height, shape, and orientation towards the main wind direction, as well as surface roughness of the surrounding area and wind speed under unprotected conditions. These parameters have been investigated by a number of researchers in temperate areas or in controlled environments (Dennyl, 1936; Kreutz, 1952; Woodruff and Zingg, 1952, p. 1–26; Müller, 1956, p. 25–28; Hagen, 1976; Wilson and Cook, 1980), but little research has so far been conducted under field conditions in the tropics.

In this experiment, the windbreaks, with their predominantly annual vegetation of 0.6-m height, led to a 20% wind speed reduction up to 10 m into the cultivated strips, which is an equivalent of 17 times the height of the annual shelterbelt vegetation. This is within the range given by Rosenberg (1974, p. 238–264) for low density shelters. In the 6- and 20-m distance treatments, the protected area covered 50% or more of the cropped surface. A sufficiently large contribution to wind protection may thus have come from the annual shelterbelt vegetation. The perennial components, however, may not have had a decisive effect, given their random occurrence and low frequency. With increasing height of the naturally occuring and planted perennials over time, this component might be more important for wind speed reduction in the wider-spaced windbreaks, but our experiment did not allow us to detect this tendency during the experiment's 3-yr duration.

With reduced wind speed, both evaporation and the amount of air-blown particles were significantly reduced. Lower potential evaporation in the most wind-protected strips could apparently not offset the increased water consumption by the shelter belt vegetation, which occupied 48% of the total surface in the 6-m windbreak distance treatment. However, significant differences in soil water content as influenced by windbreak distance treatments were only evident during the dry year, 1987, and even then only at the onset of the growing season and towards its end, when rainfall was irregular or had subsided. With field crops still absent, we detected differences in soil water content in the 0.25- to 2.70-m profile only, suggesting that water extraction occurred at greater depths than would be expected from a predominantly annual, low growing shelterbelt vegetation. Occasional bushes and trees of the natural shelterbelt vegetation as well as the planted trees may have contributed to water extraction in the narrow-spaced windbreak treatments at this range of depths. This is confirmed by the fact that soil water reserves were more depleted closer to the windbreaks than at greater distances. It thus appears that establishment of closely spaced windbreaks may put an additional strain on soil water reserves while not being required to protect emerging crops. This could become critical at the onset of the growing season in drought years.

The tested windbreaks with predominantly low growing, annual fallow vegetation spaced at 6 and 20 m, effectively reduced wind speed, potential evaporation, and amount of air-borne soil particles during planting time. With the growing season in full progress, the expanding crop cover would inevitably lead to a changed pattern of energy flux (radiation and wind) to the soil surface. An increasing crop cover would reduce transport of soil particles and evaporation at the soil surface. The protective action of the windbreaks may thus be most important during crop establishment and early crop growth. Windbreaks in our experiment provided this protection, but a sizable portion of the field was occupied by the shelter belt vegetation. This, however, may not be a problem in areas where land availability is still not limiting agricultural production.

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