Calibration of EPIC for the Simulation of Wind Erosion Damage to Pearl Millet in West Africa

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Introduction

The Sahel, the region bordering the Sahara to the south and the Sudanian zone to the north, can be defined as the region between the 100 mm and 600 mm isohyets. It comprises an area 400 to 600 km wide north-south and nearly 6000 km east-west across the African continent, touching the eight countries Senegal, Mauritania, Mali, Burkina Faso, Niger, Chad, Sudan, and Ethiopia. The population in the Sahelian zone is highly dependent on agriculture. Large parts of the arable area are cropped with pearl millet (Pennisetum glaucum (L.) R. Br.), usually in association with cowpea (Vigna unguiculata (L.) Walp.). In the traditional cropping systems in Niger, millet is sown with the first rains in May or June. Crop establishment is often poor due to extended dry periods after sowing or to sand burial due to wind erosion, which makes replantings necessary (Photo 1). The major constraints for millet yields are poor soils, lack of rainfall, high soil surface temperatures and damage by windblown sand.

The region has a monomodal precipitation pattern with rainfall occurrence between May and September. Based on daily rainfall data from Niger, it was concluded that rainfall amounts have significantly decreased since 1965, contributing to a reduction of the growing season length (Sivakumar, 1992). Arenosols or deep sandy soils occupy 29.9 million ha or 22.5% of the total area in the Sudano-Sahelian zone (Sivakumar, 1989). The textural composition of these soils is primarily sand, over 85% to a depth of 2 m or more. Besides the low soil fertility and the erratic rainfalls, wind erosion is one great constraint for crop production.

Photo 1. Poor millet establishment due to wind and water erosion.

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Several coinciding factors favor the occurrence of wind erosion. The low contents of both organic matter (<0.2%) and fine soil particles prohibit the building of non-erosive aggregates on the sandy soils. Soil crusts are sometimes formed through a cycle of rain and soil drying. The loose sand laying on such crusts is easily blown away. Texture and climatic conditions favor rapid surface drying which makes it easier for erosive forces to translocate soil material. Large planting distances for millet between 1 and 2 m, and slow crop establishment increase the damaging effects of wind.

Thunderstorms (Photo 2) occur during 10 days in the year on the average; this number increases southwards from 20-40 in the west to 80 in the Sudan (Martyn, 1992). Wind storms in the Sudano-Sahelian zone can seldom be retrieved in figures of monthly or daily wind speed averages due to their short duration of less than one hour. During the dry season from November to April, continental northeastern winds, called ‘Harmattan’, dominate. Average annual wind speed for Dakar is 7 m s^{-1} (Cochemé & Franquin, 1967) and for Niamey it is less than 2 m s^{-1} (Sivakumar, 1986). Air temperatures in the Sahelian zone vary between 18^{o}C for the mean annual minimum and 38^{o}C for the mean annual maximum (Le Houérou, 1989).

Photo 2. Sand storm in typical Sahelian parkland system.

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There was early research on the occurrence of wind erosion in the Sahel (Mainguet & Chemin, 1977); however, the role of wind erosion in the Sahelian crop production was tainted with uncertainty. At the ICRISAT Sahelian Center (ISC) in Sadoré, Southwest Niger, first field experiments on wind erosion control measures were conducted in 1985 in collaboration with the University of Hohenheim. The soils at ISC are representative of extensive areas of millet and cowpea production centers in the vicinity of Niamey, and wind erosion results can be safely extrapolated to most other areas of the sand plains and valley systems (Wilding & Daniels, 1989).N

Newly developed equipment for wind erosion measurements was made available in the late eighties that facilitated the quantification of soil flux, and that could easily be used in Sahelian millet fields.

Field and laboratory wind tunnel experiments on the extent of wind erosion in millet fields, on the damages to millet, and on the effects of appropriate control measures were conducted. The wind tunnel study on pearl millet took place in the wind erosion laboratory of the Wind Erosion Research Unit in Manhattan, KS, USA, in 1992.

The objective of the present study was a calibration and evaluation of the EPIC simulation model for the environmental and agronomic conditions of the Sahel using available data material. Specific considerations were given to damages by abrasion and burial to a growing millet crop.

The described agronomic characteristics of the semi-arid West African pearl millet production systems are a challenge for simulation efforts. Low planting densities and subsequent low LAI are difficult to handle in most models. On the other hand, no major soil tillage operation is done in the millet-dominated systems which can facilitate simulation..

The EPIC model (Williams et al., 1990), primarily developed for cropping conditions in the US, can simulate many different crops and trees including tropical species. Pearl millet, the main staple in the Sahel region, , however, was not included in the crop data file. Furthermore the low planting density, very low soil fertility conditions in traditional agricultural systems in the Sahel are difficult to simulate. On the other hand, there are not many tillage operations done in the traditional systems, a fact that may facilitate simulations of soil structure changes.

The objective of the present study was calibration and evaluation of the EPIC model for assessing abrasion and burial damages to a growing pearl millet crop, and its ability to simulate pearl millet for the environmental and agronomic conditions of the Sahel.

Material and methods

Soils and climatic data were used from ISC publications. Since its establishment in 1981 considerable amounts of basic data on effects of different cropping and management strategies on nutrient and water balance, on crop physiology and yields have been published by ISC and can be used for simulation purposes. The soils at ISC are representative of extensive areas of millet and cowpea production centers in the vicinity of Niamey, and wind erosion results can be safely extrapolated to most other areas of the sand plains and valley systems (Wilding & Daniels, 1989).

Several modifications had to be done in EPIC in order to simulate the extremely low soil phosphorus contents and the short sand storms on days with low average wind speeds. Crop coefficients for millet were developed and the extinction coefficient in the source code was adapted to the low LAI in traditional cropping systems. To simulate crop damage caused by erosive wind storms, attempts were made to integrate simple mathematical functions into the wind erosion subroutine, that could simulate both abrasion damage as well as reduction of plant stand.

Climatic data and wind erosion

Measured daily climatic data from the ICRISAT meteorological station (11 years, Jan 1984 to Nov 1994) were adapted modified to fit the EPIC format. Wind speeds had to be were converted from a 2 m to a 10 m measurement height (multiplied by 1.271) (Munn, 1966). Minimum and maximum relative humidity had to be were averaged to a mean daily value. Radiation and air temperature (min and max values) could be used in the format they were provided from the meteorological station. To run EPIC using actual rainfall data from ISC it was necessary to replace monthly average precipitation values of zero, which is common for the dry season, were replaced by a very small value greater than zero. However, EPIC did accept, however, months with no rain when measured daily data were read in.

Monthly means and standard deviations of wind speeds and directions were calculated using sample data measured in 15-minute intervals at the ICRISAT station (sample from July 94 - Dec 94). It became clear after a few test runs that EPIC did not simulate any erosion using the monthly wind speeds data and their standard deviation. This was due to the low average daily wind speeds even on days when a sand storm occurred. Observed sand storms usually lasted much less than an hour. Therefore mean wind speed and standard deviation were calculated separately for each of 16 wind direction clusters. Furthermore, a new input line was inserted into the base data set to account for an average wind erosion susceptibility (variable "uxpu") within each month. In the parameter file, parm(15) was replaced by a threshold wind speed. The EPIC source code was changed subsequently in order to handle the new detailed data format.

Soil, crop and management parameters

The dominant soil at ISC is classified as a psammentic paleustalf (sandy, siliceous, isohyperthermic) of the Labucheri soil series. Most of the model soil parameters were taken from the "Soil Survey of the ICRISAT Sahelian Center" (West et al., 1984). In the crop parameter file (CLASCROP.dat) a data set for pearl millet was added using information mainly from recent studies. The extinction coefficient was changed within the source code from a given value of 0.65 to 0.45. The value of accumulated heat units from sowing to grain harvest was estimated to be around 1800. P deficiency is known to be one of the greatest constraints to crop production in the Sahel region which was difficult to simulate with the EPIC model.. Biomass production was extremely greatly overestimated during the first simulation runs, even with low labile P contents of 3 ppm in the soil and no fertilizer use. We The modified the EPIC model was modified source code to allow extreme P deficiency and grain yields and biomass were greatly improvedto make it more sensitive to low P levels.

Management practices (sowing, weeding, harvesting) were input following common experience. Timing of each operation was specified in fraction of heat units. The EPIC model was modified so that sowing date was dependent on tIn order to simulate the sowing date in dependency from the first major rains in May or June. W, we used the option to input a soil moisture threshold in the top 0.2 m soil depth to allow germination. For the calibration runs it was assumed first that all produced residues were removed from the field after the grain harvest.

Sandblasting and burial of millet plants by blown soil

To simulate crop damage caused by erosive wind storms, empirical relationships to simulateattempts were made to integrate mathematical functions into the wind erosion subroutine, that could simulate both abrasion damage as well as and reduction of plant stand were developed and incorporated into the wind erosion subroutine. These relationships were developed using Data were taken and adapted from field and wind tunnel studies by Michels et al. (1995a,b,c). The wind tunnel study on pearl millet took place in the wind erosion laboratory of the Wind Erosion Research Unit in Manhattan, KS, USA, in 1992 (Photos 3 and 4).

Photo 3. Pearl millet seedlings in the wind tunnel at 16 days after emergence.

Photo 4. Damaged millet plants after wind tunnel treatment.

Results and Discussion

Wind erosion

Measured wind speeds and simulated wind erosion are given in Figure Fig. 1. There was an abrupt reduction in simulated erosion from 1989 onwards. After checking the measured data we found that average yearly wind speeds have nearly continouslycontinuously declined since 1985. The 1994 average wind speed was less than 1.5 m s^{-1} whereas the 1985 wind speed was 1.9 m s^{-1}. It was concluded from a within year comparison that differences were greatest during the erosion season. If this finding of decreasing wind speeds can be verified by checking with data from other weather stations, then the extent of field measured wind erosion in the may have been much higher in the eighties may have been much higher than in the nineties. Unfortunately there are no field data available on soil loss due to wind erosion from the eighties. A well calibrated EPIC could be useful in assisting to estimate the former erosion extent. The model still needs better tuning since the model underestimated erosion in the nineties which in fact was much higher than zero..

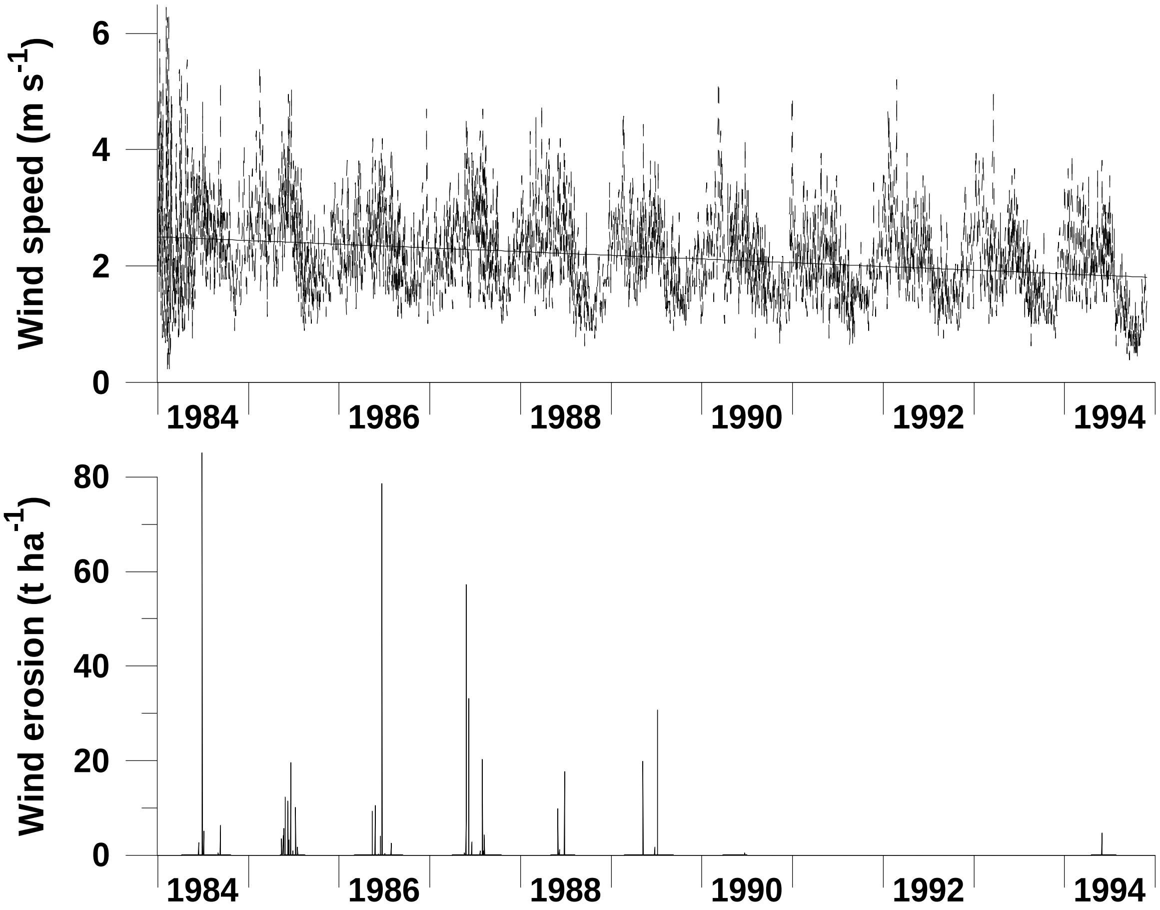

Fig. 1. Measured daily wind speeds at ISC, Niger (top), and simulated wind erosion amounts.

Millet dDry matter production

Average millet production in Niger is less than 0.5 t ha^{-1} grain yield and 1.2 t ha^{-1} stover. The simulated results in Fig. 2 are in that range. The simulated growth was sensitive to low amounts of phosphorus fertilizer. It is well established by agronomic research that millet yields can be doubled by small amounts of P fertilizer. An application of 2 t ha^{-1} crop residue increases the dry matter production of millet significantly in the field, but this not well reflected in the simulated results (Fig. 2). This may be due to the fact, that crop residue not only deliver nutrients but also increase phosphorus availability which is not simulated by EPIC. The reduction in simulated wind erosion caused by residue application was negligible whereas in field studies a 50% reduction in soil flux was determined (Michels et al., 1995b).

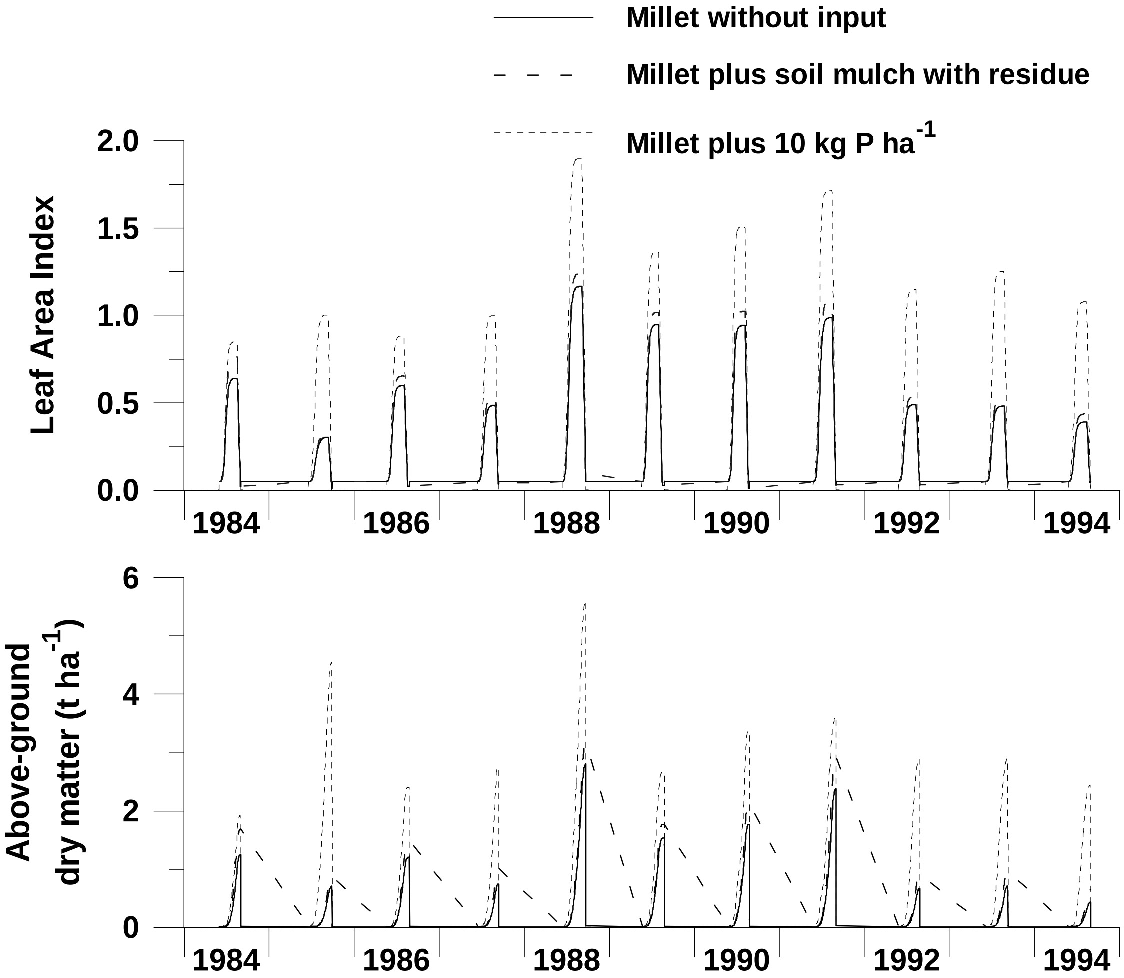

Fig. 2. Simulated leaf area index of pearl millet from 1984 through 1994 (top) and corresponding dry matter production (bottom).

Sandblasting and burial of millet plants by blown soil

In a first preliminary model abrasion damage is calculated as a reduction in actual leaf area with a linear relationship to the amount of eroded soil as given in eq. 1 and 2 (see Fig. 3). Reductions are smaller when the plant gets older or taller.

For a plant height from 0.5 to 7.5 cm:
(1) Leaf area [fraction of unexposed plant] = 0.976 - 0.0983 * wind erosion [t/ha] ($R^2 = 0.994$)

For a plant height from 7.5 cm to 15 cm:
(2) Leaf area [fraction of unexposed plant] = 0.993 - 0.0536 * wind erosion [t/ha] ($R^2 = 0.984$)

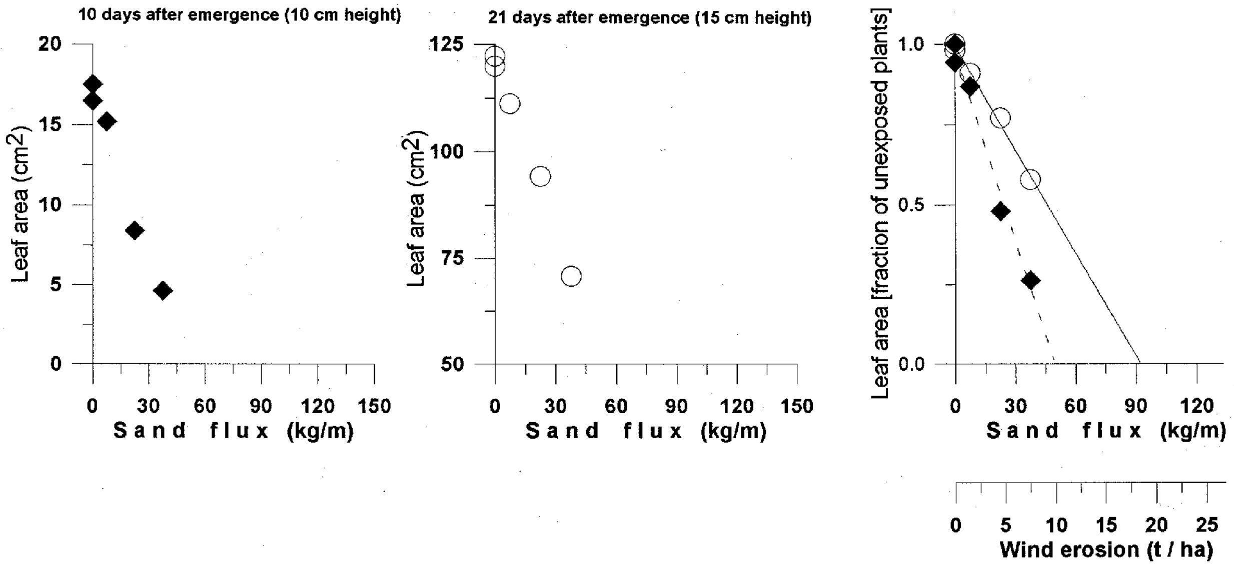

Fig. 3. Millet leaf area as affected by sand flux in wind tunnel study (Michels et al., 1995a).

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Burial damages are simulated using eq. 3, when a threshold amount of eroded soil is exceeded during one storm. Data were taken from field studies at ISC and extrapolated (Fig. 4). The burial is more pronounced when plants are small and less with taller plants. It is supposed that plants taller than 20 cm are not buried at all. Furthermore it is assumed that the severity of the burial damage depends more on plant height than on the severity of the storm. It was found that in the seedling stage even less severe storms may destroy a whole crop.

(3) Plant stand (fraction of previous plant density) = 0.38 + 0.1148 * ln (plant height, in mm)

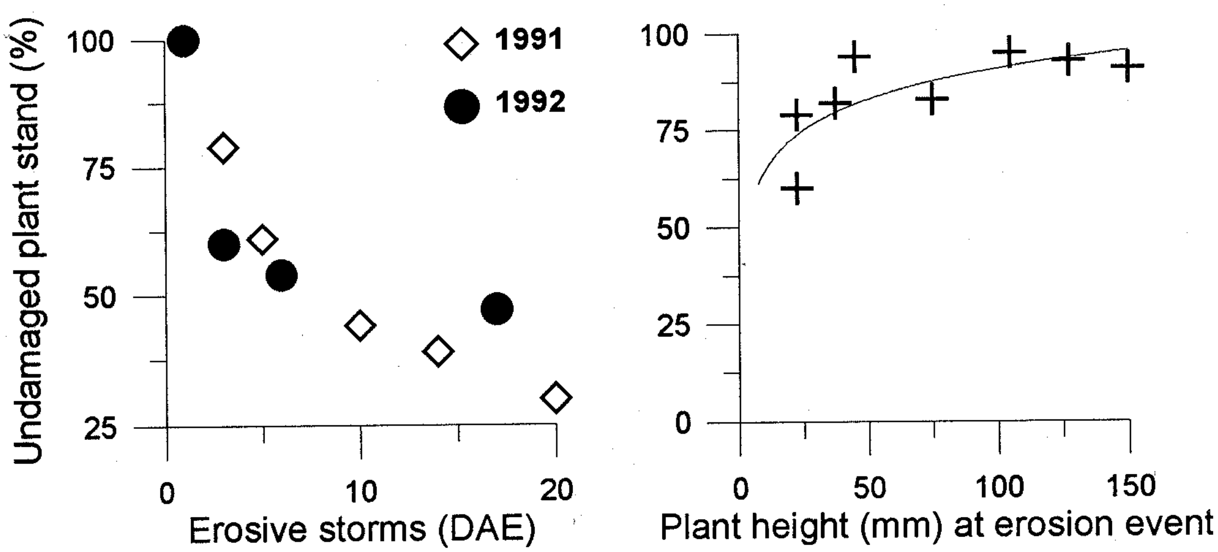

Fig. 4. Erosion damage (burial) to millet seedlings (Michels et al., 1995c)

Conclusions and outlook

The modified EPIC gave reasonable results during first test runs in simulating millet growth under the semiarid conditions in Niger. The simulation of the following different crop and soil management strategies will be the useful steps in a further validation.

- the use of fertilizer (N, P);
- the surface application of crop residue (amounts from 0.5 to 6 t/ha)
- higher plant density
- soil tillage operation (ridges)
- irrigation
- windbreaks
- rotation of millet with cowpea

A detailed verification of the simulated soil water balance using measured data need to be done in order to check if EPIC handles water stress appropriately. A major task will be the further elaboration and testing of the crop damage routine for sandblasting and burial of seedlings. Plant stress due to high soil temperatures may be an important feature to include in future work. On the long run it appears also worthy to implement an intercrop model into EPIC to simulate the traditionally common millet cowpea intercrop systems. In a future potassium subroutine, the probably significant K contribution by Saharan dust deposition could be included in the simulations. Surface crusting may also be an important feature in wind erosion modeling.

References

Cochemé, J. & P. Franquin, 1967. Etude agroclimatologique de l'Afrique sèche du Sud du Sahara en Afrique Occidentale. Projet conjoint OMN/UNESCO/FAO. FAO, Rome.

LeHouérou, H.N., 1989. The grazing land ecosystems of the african Sahel. Springer-Verlag, Berlin.

Mainguet, M. & M.C. Chemin, 1977. Les marques de l'érosion éolienne dans le Sahel du Niger d'après les images satellites et les photographies aeriennes. p 139-149 In Coll Pédol Télédétect, AISS, Rome.

Martyn, D., 1992. Climates of the World. Developments in Atmospheric Science 18. Elsevier Science Publishers, Amsterdam.

Michels, K., D.V. Armbrust, B.E. Allison & M.V.K. Sivakumar, 1995a. Wind and windblown sand damage to pearl millet. Agronomy Journal 87:620-626.

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

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

Munn, R.E., 1966. Descriptive meteorology. Academic Press, New York.

Sivakumar, M.V.K., 1989. Agroclimatic aspects of rainfed agriculture in the Sudano-Sahelian zone. p 17-38 In Soil, crop, and water management systems for rainfed agriculture in the Sudano-Sahelian zone. Proc Int Workshop, 7-11 Jan 1987. Niamey. ICRISAT, Patancheru, A.P. 502324.

Sivakumar, M.V.K., 1992. Climate change and implications for agriculture in Niger. Climatic Change 20:297-312.

West, L.T., L.P. Wilding, J.K. Landeck & F.G. Calhoun, 1984. Soil survey of the ICRISAT Sahelian Center, Niger, West Africa. Texas A&M University/TropSoils, College Station, TX.

Wilding, L.P. & R.D. Daniels, 1989. Soil-geomorphic relationships in the vicinity of Niamey, Niger. TropSoils Bulletin No. 89-01. Soil Management Collaborative Research Support Program, Raleigh, NC.

Williams, J.R., P.T. Dyke, W.W. Fuchs, V.W. Benson, O.W. Rice & E.D. Taylor, 1990. Erosion/productivity impact calculator: 2. User manual. In Sharply AN & Williams JR (ed.). U.S. Dept. of Agriculture Technical Bulletin No 1768.Mainguet M & Chemin MC 1977 Les marques de l'érosion éolienne dans le Sahel du Niger d'après les images satellites et les photographies aeriennes. p 139-149 In Coll Pédol Télédétect, AISS, Rome

Martyn D 1992 Climates of the World. Developments in Atmospheric Science 18. Elsevier Science Publishers, Amsterdam

Michels K Armbrust DV Allison BE Sivakumar MVKS 1995a Wind and windblown sand damage to pearl millet. Agronomy Journal 87:620-626

Michels K Sivakumar MVK Allison BE 1995b Wind erosion control using crop residue I. Effects on soil flux and soil properties. Field Crops Research 40:101-110

Michels K Sivakumar MVK Allison BE 1995c Wind erosion control using crop residue II. Effects on millet establishment and yield. Field Crops Research 40:111-118

Sivakumar MVK 1989 Agroclimatic aspects of rainfed agriculture in the Sudano-Sahelian zone. p 17-38 In Soil, crop, and water management systems for rainfed agriculture in the Sudano-Sahelian zone. Proc Int Workshop, 7-11 Jan 1987. Niamey. ICRISAT, Patancheru, A.P. 502324

Sivakumar MVK 1992 Climate change and implications for agriculture in Niger. Climatic Change 20:297-312

West LT, Wilding LP, Landeck JK & Calhoun FG 1984 Soil survey of the ICRISAT Sahelian Center, Niger, West Africa. Texas A&M University/TropSoils, College Station, TX

Williams JR, Dyke PT, Fuchs WW, Benson VW, Rice OW & Taylor ED 1990 Erosion/productivity impact calculator: 2. User manual. In Sharply AN & Williams JR (ed.). U.S. Dept. of Agriculture Technical Bulletin No 1768