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Wind erosion modelling in a Sahelian environment

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Abstract

In the Sahel field observations of wind-blown mass transport often show considerable spatial variation related to the spatial variation of the wind erosion controlling parameters, e.g. soil crust and vegetation cover. A model, used to predict spatial variation in wind erosion and deposition is a useful tool in the implementation of wind erosion control measures in the Sahel. The aim of this paper was to test two existing wind erosion models on spatial predictions of aeolian mass transport for Sahelian conditions. Field data from Burkina Faso were used to test an empirical (RWEQ) and a deterministic (WEPS) model.

The revised wind erosion equation (RWEQ) poorly predicted maximum mass transport and so spatial predictions of mass transport were underestimated. Major constraints of RWEQ for application in the Sahel were the required non-eroding boundary and the fact that RWEQ assumes a more or less homogeneous field. It was concluded that RWEQ in its current state was not suitable for application in a Sahelian environment.

With the correct roughness length (Z0), wind erosion prediction system (WEPS) correctly predicted friction velocity and initiation and cessation of mass transport. Furthermore, the model gave a reasonable prediction of the spatial distribution of mass transport at the research sites. It was concluded that WEPS in PCRaster is suitable for prediction of wind erosion in a Sahelian environment. A constraint of WEPS in PCRaster is that WEPS' predictions of spatial variation in sediment transport are closely linked to the spatial variation in the input parameters. A good estimation of the spatial variation of the input parameters was required. Obtaining these might be an expensive exercise and could make its use in the Sahel difficult.

Software availability

RWEQ:

First release:	June 1998
Contact:	Dr. Ted Zobeck, USDA-ARS, 3810 4th Street, Lubbock, TX, USA
Free download from:	http://ww.csrl.ars.usda.gov/wewc/rweq/rweq.htm

Works in DOS environment

WEPS

First release:	1995
Contact:	USDA-ARS, NPA, Wind Erosion Research Unit, 1515 College Avenue, Kansas State University, Manhattan, KS 66600, USA
Free download from:	http://www.weru.ksu.edu/new_weru/weps/weps.html

Works under UNIX and Windows

PCRASTER

First release:	1991
Contact:	PCRaster Environmental Software, PO Box 427, 3500 AK Utrecht; The Netherlands
Free download from:	http://www.pcraster.nl

Works under DOS, Windows and LUNIX

1. Introduction

Approximately 90% of the inhabitants of the Sahelian zone of Africa (a zone of approximately 200–400 km wide, centred on latitude 15° N) live in small villages and depend on subsistence agriculture for a living

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(Thiombiano, 2000). Due to rapid population growth, the cropping area has expanded to more marginal lands and the fallow period has been shortened or even abandoned (Thiombiano, 2000). Consequently, the combination of continuous soil erosion and the overexploitation has resulted in large scale degradation of soil productivity (Dregne, 1990). The already low fertile Sahelian soils have in general a sandy or sandy loam texture and are prone to wind erosion, especially in the early rainy season, when soils are bare and unprotected (Bielders et al., 2001; Boiffin and Bresson, 1987; Casenave and Valentin, 1989; Michels et al., 1995; Sterk, 1997, 2003; Thiombiano, 2000). The semi-arid climate of the Sahel has a long dry season from October until May and a short rainy season from June until September. In the early rainy season, when rainfall occurs in heavy thunderstorms, strong dust storms may develop. These events are usually short-lived, but may transport large amounts of sediment (Bielders et al., 2002; Michels et al., 1995; Sterk et al., 1996; Sterk and Stein, 1997; Visser et al., in press). Wind erosion contributes to soil degradation by removal of the nutrient rich topsoil (Lal, 1988). Furthermore, crop seedlings suffer from abrasion or burial by sand during these early rainy season events (Michels et al., 1995; Sterk, 1997). The damage to crops ranges from reduced or delayed growth to its complete destruction. In order to prevent large-scale famine, it is of the utmost importance to control crop damage and soil degradation by wind erosion in the Sahel. However, in the Sahel, soil conservation possibilities are limited. A wind erosion model can be a useful tool in the battle against wind erosion since it can predict wind erosion risk under various land management practices. Then the best wind erosion preventing practices can be selected, tested and finally applied in the field.

Several researchers have shown that soil degradation by wind erosion in the Sahel cannot be defined as a total soil loss per hectare due to a large spatial variation in erosion and deposition at the scale of a field (Bielders et al., 2001; Sterk and Stein, 1997; Visser et al., in press). However, most available wind erosion models do predict erosion in terms of total soil loss per hectare. Especially in a Sahelian environment, factors that determine the erodibility of the soil for wind erosion (e.g. vegetation cover, land management and crust type) are distributed over the area, resulting in a spatial variation of erosion and deposition even when measuring at the scale of a field. Therefore, a wind erosion model, suitable for the Sahelian situation, should at least have a spatial component to be able to deal with the spatial variation in input parameters and to predict the spatial pattern of erosion and deposition.

In the Sahel, crust or crust-like surfaces are omnipresent characteristics of the soils (D'Herbès and Valentin, 1992). Their type and structure are not only determined by soil texture but also by erosion and deposition by wind and water and by vegetation. Their distribution in the field further depends on terrain position and microrelief (Graef and Stahr, 2000). Each crust type has unique characteristics for thickness, resistance and availability of loose material and so has an unique influence on the wind erosion process. The following example illustrates the key-role of crust development in wind erosion. Consider, e.g. the first rainfall on a freshly tilled Sahelian field. This usually leads to the formation of a structural sieving crust consisting of a plasmic seal overlain by loose sand (Valentin and Bresson, 1992). This loose sand is available for transport by wind, leaving the plasmic layer uncovered, resulting in an erosion crust. The sediment under this erosion crust is excluded from the wind erosion processes and only becomes available when the crust is broken. Therefore, wind erosion models applicable in a semi-arid environment like the Sahel should account more for the distribution of the various crust types (Valentin, 1995).

The aim of this paper was to test two existing wind erosion models, an empirical and a physical model, on their spatial predictions of aeolian mass transport at the scale of a field under Sahelian conditions. The performance of the two models will be tested with field data from the 2001 wind erosion measurement campaign in the Katchari catchment, northern Burkina Faso.

2. Materials and methods

2.1. RWEQ

The USDA-Agricultural Research Service first released the revised wind erosion equation (RWEQ) in 1998 (Stout, 2003). Here, only the key processes and equations of the RWEQ model are given, for a detailed description of the model and the measurement techniques of the different input parameters, the reader is referred to Fryrear et al. (1998b). The RWEQ makes estimates of soil eroded and transported by wind between the soil surface and a height of 2 m for specified periods based on a single-event wind erosion model.

Fine sediment is generally transported as suspended load and travels over much larger distances than the coarse sediment, which is generally transported in creep or saltation mode. RWEQ is best applicable for predicting erosion at field scale but also provides information on erosion rates within the field (Fryrear et al., 1998a). The simulation area is a circular or rectangular field bounded by a non-eroding boundary. The model calculates aeolian mass transport within the field from the balance between wind erosivity and soil erodibility. For this, the following equation is used (Fryrear et al., 1998b):

$$Q(x) = Q_{\text{maxp}}\left[1 - e^{-(x/s_p)^2}\right] \quad (1)$$

where x (m) is the downwind distance from the non-eroding boundary, Q_{maxp} (kg/m) is the transport capacity and s_p (m) is the distance where 63% of the maximum transport capacity is reached, called the critical field length (Fig. 1). The assumption of a non-eroding boundary around the field implies that the highest soil losses will occur in the zone just downwind of the non-eroding boundary.

The transport capacity (Q_{maxp}) and the critical field length (s_p) are determined by several factors: weather (WF), single soil roughness (K'), combined crop (COG), crust (CF) and the erodible fraction of the soil (EF) (Fig. 2).

The WF is a function of the wind factor (Wf), soil wetness (SW) and snow depth (SD) (Fig. 2). The wind factor is calculated from wind speed measurements at a height of 2 m and soil wetness is a function of rainfall history and solar radiation. K' is a function of oriented and random roughness, measured with the chain of Saleh (1993) and the COG is determined by the dead, lying and standing vegetation cover and the living crop cover.

The erodible fraction (EF) of the soil was calculated using Eq. (2) (Fryrear et al., 1998b):

$$\mathrm{EF} = \frac{29.09 + 0.31\mathrm{SA} + 0.17\mathrm{Si} + 0.33\dfrac{\mathrm{SA}}{\mathrm{CL}} - 2.59\mathrm{OM} - 0.95\mathrm{CaCO_3}}{100} \quad (2)$$

where SA is the sand content (%), Si is the silt content (%), SA/CL is the sand to clay ratio, OM is the organic matter content (%) of the soil and $CaCO_3$ is the calcium carbonate content (%).

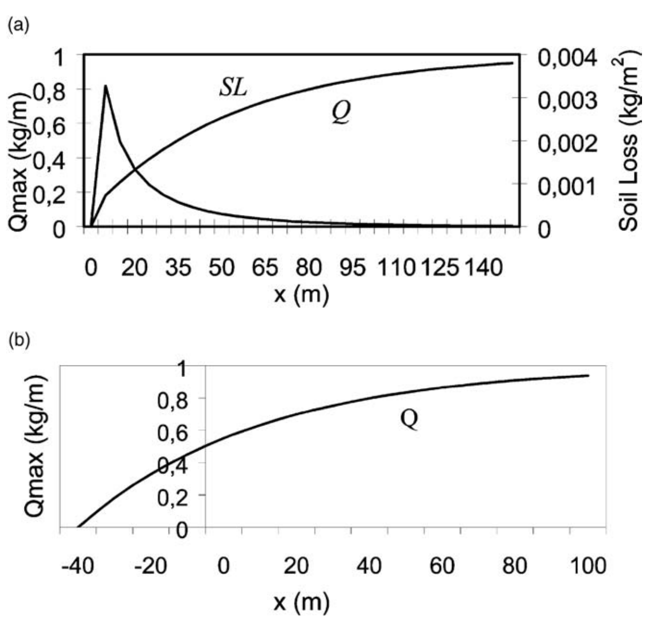

Fig. 1. (a) Relationship between mass transport (Q) and soil loss (SL) from RWEQ using critical field length $s = 50$m and maximum mass transport $Q_{max} = 1$kg/m (Fryrear et al., 1998b). (b) Relationship between mass transport and field length, the curve is transposed over distance $\alpha = 50$m using Eq. (9).

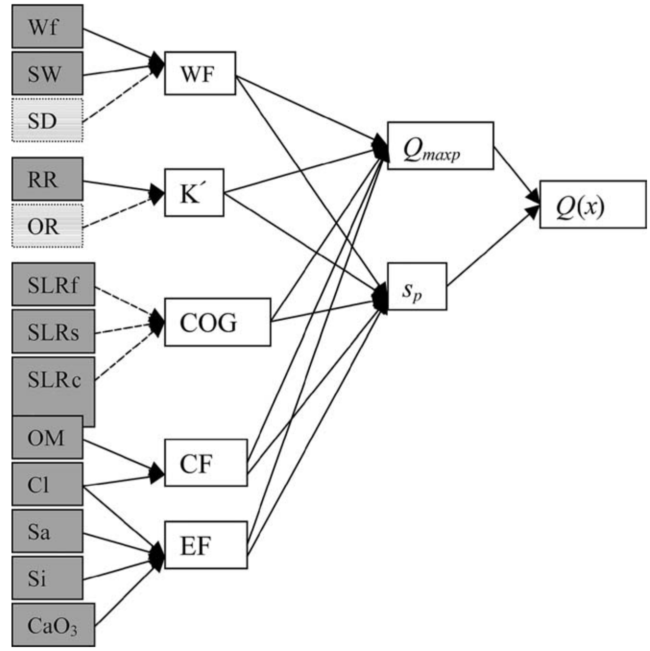

Fig. 2. Schematic overview of the calculation procedure for mass transport in the RWEQ model. Grey boxes are the input parameters. Parameters in dashed boxes are not included for application in this research. WF, weather factor; Wf, wind factor; SW, soil wetness; SD, snow depth; K', single soil roughness factor; RR, random roughness; OR, orientated roughness; COG, combined crop factors; SLRf, -s and -c, flat residue, standing residue and crop cover; CF, crust factor; EF, erodible fraction; OM, organic matter; CL, clay content; Sa, sand content, Si, silt content and $CaCO_3$, calcium carbonate content.

The soil crust factor (SCF) was defined as a function of percent clay (CL) and organic matter content, using Eq. (3) (Fryrear et al., 1998b):

$$\mathrm{SCF} = \frac{1}{1 + 0.0066(\mathrm{CL})^2 + 0.021(\mathrm{OM})^2} \quad (3)$$

The range of values in the calibration data set of the RWEQ model is given in Table 1; Eqs. (2) and (3) have not been verified for values outside these ranges.

All the factors are combined in Eqs. (4) and (5) to calculate values for Q_{max} and s.

$$Q_{maxp} = 109.8(\mathrm{WF} \cdot \mathrm{EF} \cdot \mathrm{SCF} \cdot K' \cdot \mathrm{COG}) \quad (4)$$

$$s_p = 150.7(\mathrm{WF} \cdot \mathrm{EF} \cdot \mathrm{SCF} \cdot K' \cdot \mathrm{COG})^{-0.317} \quad (5)$$

2.2. WEPS

The USDA-ARS first released a beta version of the wind erosion prediction system (WEPS) in 1995 (USDA-ARS, 1999a,b). Since then the model has had several updates. WEPS is a process-based, daily time-step computer model that predicts soil erosion through

Table 1
Range of values in calibration data set of RWEQ. Outside these ranges, Eqs. (2) and (3) have not been verified. SA, sand content; Si, silt content; CL, clay content; OM, organic matter content; and $CaCO_3$, calcium carbonate content

	SA (%)	Si (%)	CL (%)	SA/CL	OM (%)	$CaCO_3$ (%)
Range	5.5–93.6	0.5–69.5	5.0–39.3	1.2–53.0	0.18–4.79	0.0–25.2

simulation of the physical processes that control wind erosion (Hagen, 1991). Here, only the key processes and equations of the WEPS model are given, for a detailed description of the model and the measurement techniques of the input parameters, the reader is referred to Hagen (1996a). WEPS has a modular structure, including a weather simulator, and simulates apart from the basic wind erosion processes, surface condition, crop growth, residue decomposition, soil aggregates and crust status, hydrology and management. When wind speed exceeds the threshold for erosion, the erosion sub-model simulates erosion on a sub-hourly basis. Whereas the full model is more suitable for wind erosion predictions on larger time scales, the stand-alone erosion sub-model is suitable for the erosion modelling at the scale of an event (i.e. daily). The erosion sub-model considers the simulation area to be a rectangular field and composed of one or more sub-regions with different surface conditions for soil, management or cropping. The simulation field is divided into grid cells; each grid cell needs to contain information about the following surface conditions: (1) surface roughness: random and oriented roughness below the biomass canopy, (2) soil cover: flat, random biomass cover, crust with loose erodible particles, aggregated soil and rock cover, (3) surface soil moisture and (4) standing biomass.

The erosion sub-model is divided into several major functional components to accomplish the following simulation objectives (Fig. 3): to calculate the friction velocities for each cell (U^*), to calculate threshold friction velocities for each cell (Wust) and if sediment transport occurs (U^*/Wust > 1) to compute soil loss/deposition in each cell and finally to update surface variables changed by erosion and output the selected information files. The driving force of the WEPS model is the excess of friction velocity (U^*) above the threshold friction velocity (Wust) (Fig. 3). The friction velocity at the weather station is calculated using (Hagen, 1996a):

$$U_{\mathrm{w}}^* = \frac{0.4\mathrm{WS}}{\ln\left(\dfrac{h\mathrm{WS}}{Z0_{\mathrm{w}}}\right)} \tag{6}$$

where U_{w}^* is the friction velocity at the weather station (m/s); WS is the wind speed (m/s); hWS is the height of wind speed measurements (mm) and $Z0_{\mathrm{w}}$ is the roughness length at the weather station.

If the weather station is not situated at the simulation field, the friction velocity at the simulation field is calculated with (Hagen, 1996a,b):

$$U_{\mathrm{p}}^* = U_{\mathrm{w}}^* \left(\frac{Z0_{\mathrm{p}}}{Z0_{\mathrm{w}}}\right)^{0.067} \tag{7}$$

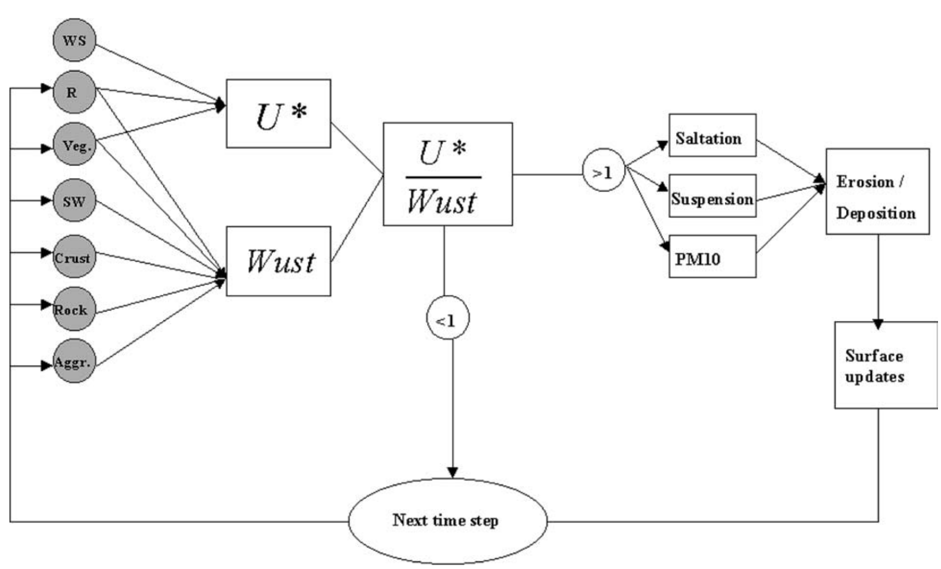

Fig. 3. Schematic overview of the calculation procedure for mass transport in the WEPS model. Grey boxes are the input parameters. After an erosive time step, all input parameters, except wind speed are updated based on the net erosion/deposition in a grid cell. WS, wind speed (m/s); R, roughness parameters, including random and oriented roughness; Veg, vegetation coverage including flat and standing biomass (m^2/m^2); SW, soil wetness (kg/kg); Cust, crust parameters, including soil fraction crusted and fraction loose erodible particles; Rock, fraction of rock coverage; Aggr, aggregate parameters, including aggregate strength (Ln (J/kg)) and size (μm); U^*, friction velocity (m/s); Wust, threshold friction velocity for entrainment (m/s); and PM10, particle matter < 10 μm.

where U_p^* is the friction velocity at the simulation field (m/s) and $Z0_p$ is the roughness length at the simulation field (mm). The friction velocity at the simulation field is further influenced by the presence of windbreaks. The roughness length at the simulation field is calculated based on aerodynamic roughness of ridges, random roughness and standing biomass canopy (Fig. 3).

WEPS calculates two different values for the threshold friction velocity, one for entrainment (Wust) and one for transport (Wusp) based on Bagnold's theory on fluid and impact threshold (Bagnold, 1941). For soils with a sandy texture, the impact threshold velocity is generally lower than the fluid threshold velocity. WEPS calculates the threshold friction velocities based on input parameters for the fraction of bare emitting soil surface, flat biomass cover, soil wetness and aggregate size and density. For erosion to occur, U^* needs to become larger than Wust ($U^*/\text{Wust} > 1$). Later, when wind speeds drop, but U^* is larger than Wusp ($U^*/\text{Wusp} > 1$), theoretically transport is still possible. However, in WEPS, if a grid cell is not erosive ($U^*/\text{Wust} < 1$) and transport is possible ($U^*/\text{Wusp} > 1$), sediment flowing into the cell is first deposed and in the next time step this deposited, loose sediment can be eroded. The model developers used this strategy to enhance model speed. When time steps are sufficient small (< 1 s), this strategy should not result in errors in prediction of sediment transport.

When it is established that erosion is possible, the transport capacity using the emission threshold capacity (qen) and the transport threshold capacity (qcp) are calculated as follows (Hagen, 1996a,b):

$$\text{qen} = \text{CS} \cdot U^{*2}(U^* - \text{Wust}) \tag{8a}$$

$$\text{qcp} = \text{CS} \cdot U^{*2}(U^* - \text{Wusp}) \tag{8b}$$

where qen is the transport capacity using the emission threshold capacity (kg m^{-1} s^{-1}); qcp is the transport capacity using the transport capacity threshold (kg m^{-1} s^{-1}); CS is the saltation transport coefficient (kg s^2 m^{-4}), fixed at 0.3. The transport capacities are later used to calculate the input and output sediment fluxes of the grid cells. WEPS separately calculates the saltation/creep, suspension and PM10 (particle size ≤ 10 μm) components of the eroding material, based on the size distribution of the topsoil and the soil surface characteristics. From the in- and outgoing sediment fluxes, net erosion or deposition in the grid cell is calculated. Finally, the surface variables changed by erosion and deposition are updated.

2.3. Field measurements

During the early rainy season of 2001, field data for wind erosion events were collected at three sites in the Katchari catchment in northern Burkina Faso (14° 00′ N, 0° 00′ W). The Katchari catchment covers an area of 12 km^2 and is situated in the province of Seno, 11 km west from Dori, the provincial capital. The climate is characterised by a short rainy season of 3–4 months. Mean annual precipitation is 480 mm, but highly variable from year to year. Temperatures are high all year round. Generally, the first rains come from the east. Those rains are often preceded by windstorms, which may cause severe wind erosion.

The research sites were chosen so that they each had a different geomorphologic setting: a degraded site, a valley floor and a dune (Table 2). The degraded site is characterised by its lack of vegetation and a strong gravel crust (Valentin and Bresson, 1992). The south-eastern part of the research plot at the degraded site is bordered by a dry streambed, with a depth of approximately 20 cm and a width of 1.5 m. The valley floor is incised by a river, which is dry in the dry season and may flood during the wet season. The research site at the valley floor is cultivated with millet in the wet season and characterised by fast development of erosion and still depositional crusts (Valentin and Bresson, 1992). Natural vegetation (trees and herbs) are scattered over the field. Annual herbs are removed by hoeing twice in the wet season. The borders of the field at the dune are demarcated with trees, however these trees do not form a continuous row as in a wind barrier. Several shrubs can be found inside the dune site and, similar to the valley floor, annual herbs are removed twice a year and the field is cultivated with millet. The dune is part of an old and flattened dune band that belongs to an extensive sand dune system, which is more than 40.000 years old (Courel, 1977). The loamy, sandy soils of this dune complex are prone to crusting, with structural and erosion crusts being the most common (Valentin and Bresson, 1992).

Table 2
Surface soil characteristics of the dune site, the site at the valley floor and the degraded site in the Katchari catchment, Burkina Faso. All parameters are determined following a procedure as suggested by Fryrear et al. (1998b)

Location	Texture	Sand (%)	Silt (%)	Clay (%)	Organic matter (%)	Calcium carbonate (%)
Dune	Loamy sand	84.4	12.6	3	0.16	0.23
Valley floor	Loamy sand	79.1	15.8	5.1	0.47	6.9
Degraded site	Clay loam	59	19.4	21.6	0.3	7.9

All fields are characterised by an undulating topography. Maximum height differences within the site on the dune were approximately 0.5 m. At the valley floor and the degraded site, the distances between depressions and crests ranged from 10 to 40 m with maximum height differences of approximately 1 m.

At each site, a plot of 80×80 m was selected and instrumented with 17 modified Wilson and Cook (MWAC) sediment catchers. The catchers were regularly distributed in circles so that in each of the main wind directions, a line of five catchers was formed. In one line, the catchers were 15 m apart. For each site and each event, total mass transport was determined by sampling mass flux densities at five heights (0.07, 0.14, 0.22, 0.28 and 0.75 m) and integrating over the height. Sterk and Raats (1996) gave a description of the MWAC catchers and a method for quantifying total mass transport (kg/m) from the trapped material. The research was set up to measure actual sediment transport in farmers fields, so the vegetation was not removed before the placement of the catchers. Clear, non-eroding boundaries could not be identified in the selected sites, and thus saltation and creep particles could freely enter the sites.

At the dune and the degraded site, weather stations were installed. Since the research plot at the valley was situated less than 500 m from the degraded site, weather data from the degraded site was used for the valley. Wind speed and wind direction were measured at 1-min intervals at a height of 2 m. At the degraded site, a wind profile was measured at 0.5, 1, 2 and 3 m. All meteorological equipment was set up in such a way that easterly winds were non-disturbed by obstacles. Soil wetness was measured at 5-min intervals with a water content reflectometer (Campbell, 1999), placed horizontally at a depth of approximately 2 cm. Moments of initiation and cessation of mass transport were determined with saltiphones, which is an acoustic saltation sensor that records particle impacts with a microphone (Spaan and Van den Abeele, 1991).

In the dry period, the input parameters, roughness and vegetation characteristics were determined once a month, in the wet period once a week. The input parameters were measured according the methods advised by Fryrear et al. (1998b) and Hagen (1996a). For each of these input parameters, 15 measurement points were randomly distributed over the research plot. In a circle of 2 m around a measurement point, five measurements for each parameter were made. Inversed distance interpolation was used to prepare maps of the necessary input parameters.

2.4. Additional data for testing WEPS

The values for U^*_m and $Z0_m$ were calculated from a measured wind profile following a procedure described by Stull (2001). A wind profile was measured only at the degraded site (with anemometers at heights of 0.5, 1.0, 2.0 and 3.0 m). To prevent basing conclusions on data from one research site only, the capability of WEPS (implemented in a spatial modelling language) to correctly predict U^*_p, $Z0_p$ as well as moments of initiation and cessation of wind-blown mass transport were further tested with wind profiles and erosion data from other sites in the Sahel (Sterk, 1993 and Leenders, unpublished, 2002). The research site of Sterk (1993) was situated at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Center at Sadore, in Niger, 40 km south of the capital Niamey. The wind field at this site was not disturbed by obstacles like wind breaks and buildings. The research site had a mulch cover of 5% and no living vegetation.

Additional wind profile data came from two research plots of Leenders that are situated at traditionally cultivated fields near the village Windou, in Burkina Faso, 8 km west of the province capital Dori. The meteorological equipment was set up in such a way that easterly winds were non-disturbed. Windou-bare was a bare field and Windou-mulch had a mulch cover of 0–3%. Natural vegetation was present at both fields and Windou-mulch was used for cropping with pearl millet (sowing date 4 June 2002).

In this paper, parameters measured in the field or calculated from field measurements are indicated with subscript m, whereas model results are indicated with subscript p.

2.5. Model adaptations

2.5.1. RWEQ

For the USA, weather data files are available, which describe wind with the monthly Weibull cumulative probability distribution, using coefficients k (shape) and c (Weibull scale) and percentage calm (Skidmore and Tatarko, 1990). Using this information, the RWEQ program simulates wind speeds for the simulation site. For the Sahelian region, extended weather data files are not available. The RWEQ model does not directly give output information on mass transport over the field. So, to obtain this information and to be able to work with measured wind speed data during one event as input, an EXCEL worksheet, containing all RWEQ equations was created.

For determination of Q_{maxp} and s_p, snow depth (SD) and oriented roughness (OR) were left out of consideration since these parameters were not present (Fig. 2). Furthermore, in the Sahel, fields are not surrounded by non-erodible boundaries. A single tree, a path or rocks often indicate the edges of the fields. None of our research plots had a non-erodible boundary, so we do not know exactly at which point in the predicted plot

(Fig. 1(A)) the measurements were made. Therefore, Eq. (1) was adjusted to fit the available data by transposing the sigmoid curve over distance α (Eq. (9)).

$$Q(x) = Q_{\mathrm{maxm}}\left[1 - \mathrm{e}^{-(x+\alpha/s_{\mathrm{m}})^2}\right] \tag{9}$$

The curve will cross the y-axis at point (0, Q), the first field measurement, and cross the x-axis at point ($-\alpha$, 0) (Fig. 1(B)). Following a procedure suggested by Zobeck et al. (2001), Q_{maxm}, s_{m} and α are calculated from the field measurements by performing least squares, non-linear regression analysis using Eq. (9). Based on the wind direction, mass flux data of five sediment catchers were selected from the available sediment catchers.

The measured (using Eq. (9)) and predicted (using Eqs. (4) and (5)) values of Q_{max} and s are compared to see if the RWEQ is applicable on the Sahelian situation. If a good correlation between predicted and measured values is reached, mass transport (Q) in the field can be estimated using Eq. (9) and compared with the measured mass transport values of the selected catchers in the field.

2.5.2. WEPS

The current version of WEPS (1.0) can only handle a single homogeneous sub-region (Wagner, 2002). To account for the spatial variation of the input parameters in a Sahelian environment, the programming code of WEPS 1.0 was translated into the dynamic modelling language of PCRaster (De Jong, 1997), which is an environmental modelling language embedded in a GIS (Karssenberg, 2002). Another advantage of incorporating WEPS into PCRaster is the relatively open data structure of PCRaster, which permits the user to closely follow the erosion simulation.

Here, we tested the WEPS in PCRaster on the correct prediction of three parameters, which are important in determining the total erosion/deposition on a field. First, the model was tested on the prediction of the friction velocity, since this parameter was crucial in the model equations. For several events and different measurement fields, the U^*_{m} and $Z0_{\mathrm{m}}$ were determined from the measured wind profile and these were compared with the $Z0_{\mathrm{p}}$ and the average U^*_{p} predicted by WEPS. Since the measured $Z0_{\mathrm{m}}$ is based on the average roughness of the soil surface upwind from the weather station, we compared the measured value with the average $Z0_{\mathrm{p}}$ of the field till 80 m (field length of the research site) upwind from the weather station. The U^*_{m} is an average for the whole event and is therefore compared with the average U^*_{p} of the event.

Furthermore, we tested whether the model correctly predicted the moment of initiation and cessation of sediment transport. These are important moments since the total duration of a wind erosion event is one of the key parameters in the calculation of total sediment transport.

To see whether WEPS correctly predicted moments of initiation and cessation of mass transport, we compared the ratio of $U^*_{\mathrm{p}}(t)/\mathrm{Wust}$ with measured saltiphone data. If the ratio was larger than one, sediment entrainment is possible and should correspond with the saltiphone data. Since the saltiphone gives an indication of the intensity of mass transport at one point in the field, while mass transport is a spatial variable in the field, average values of 4×5m upwind from the position of the saltiphone for U^*_{p} and Wust were used for the comparison. We chose this 4×5m to account for the influence of roughness elements in the upwind direction.

Finally, the model was tested on the correct prediction of the spatial distribution of mass transport. Field measurements of total mass transport (kg/m) were compared with WEPS output mass transport in kg/m. For the prediction of mass transport, some adjustments to the WEPS erosion sub-model were made in the PCRaster script. First of all, since no non-eroding boundaries were present, input of sediment was a necessary boundary condition. To meet this boundary condition, the simulation area was placed in the centre of an area three times its size. Soil and soil cover characteristics of the boundary area were set to the average of the simulation area. To avoid sediment depletion, sediment flowing out at the downwind boundary of the larger area at one time step, was blown in at the upwind boundary of the larger area in the next time step. The main advantage of re-using sediment over a constant input of sediment is that because wind speed was variable, transport capacity was variable and so a better estimation of incoming sediment was obtained.

Furthermore, the assumption of WEPS that saltation transport is only possible when erosion can occur ($U^*_{\mathrm{p}}(t)/\mathrm{Wust} > 1$ and qen > 0 (Eq. (8a))) is adjusted. The grid size in original WEPS is sufficiently large to justify this assumption. This is because saltation transport becomes less and less intense when no new saltation particles are added to the sediment stream (Livingstone and Warren, 1996). However, during this study, grid size was 1 m^2. So when at a certain grid cell no erosion was possible ($U^*_{\mathrm{p}}(t)/\mathrm{Wust} < 1$), the incoming sediment flux could be transported if $U^*_{\mathrm{p}}(t)/\mathrm{Wusp} > 1$. In this case, the outgoing sediment flux was at its maximum equal to the transport capacity, qcp (Eq. (8b)).

3. Results and discussion

In the 2001 rainy season, 11 wind erosion events occurred in the Katchari catchment and three of them were followed by heavy rainfall. In general, the first

Table 3
Date, duration (D), average wind speed (WS) at 2 m, wind direction (wdir) and average and range of mass transport at the degraded plot and the dune and average and range of mass transport at the valley in the Katchari catchment, Burkina Faso, 2001 rainy season

Date	Dune					Degraded plot					Valley	
	D (s)	WS (m/s)	wdir	*Q* (kg/m)	Range (kg/m)	*D* (s)	WS (m/s)	wdir	*Q* (kg/m)	Range (kg/m)	*Q* (kg/m)	Range (kg/m)
20 May	1680	8.3	N	49.6	4–57.7	1620	7.7	N	–	–	32.6	4.6–75.6
22 May	1740	8.1	S	72.9	31.1–120.9	1560	8.6	S	13.6	4.9–25.8	88.3	20–169.9
3 June	2280	7.2	SE	59.4	26.6–59.4	840	7	SE	4.6	1.6–16.3	20.5	1.4–47.9
9 June	2160	8.8	NE	119.1	52.7–206.2	1260	9.3	ENE	12.2	5.5–29.8	54.8	19–122.9
19 June	2760	9.0	E	136.3	47.1–269.4	2400	8.5	E	50.6	21.7–109.1	43.8	13–129.3
22 June	1260	9.2	E	100.7	8.1–182.8	1140	11.8	E	43.4	9.8–96.2	56.1	15–157.8
29 June	220	7.5	N	53.6	12.9–74.2	220	8.6	N	10.6	2.1–38.4	17.8	5.3–43.1
3 July	1200	7.4	N	40.7	8.5–87.7	1140	7.5	N	15.9	4.0–34.7	51.0	17.2–84.2
10 July	1500	9.0	SE	69.3	44.5–113.8	1320	9.5	SE	28.6	6.6–103.3	51.0	14–141.2
11 July	2580	8.4	NE	36.1	5.8–77.9	2280	9.5	NE	13.7	6.7–32.5	8.4	1.3–16.9
13 July	1560	8.2	NE	40.9	9.4–69.2	1500	9.9	NE	49.2	19.5–96.1	47.3	14–102.8

thunderstorms move from east to west, hence wind direction during a wind erosion event is easterly, but it can be variable depending on the site location relative to the centre of the storm (Sterk and Stein, 1997). The wind direction of the 11 sampled events varied from north to south, average wind speed ranged from 7 to 11.9 m/s, and the total duration of the events ranged from 220 to 2760 s (Table 3). During the event of May 20, the catchers of the degraded sited were malfunctioning; therefore, these data were not used for modelling. Generally, most sediment transport occurred at the dune site and least sediment transport occurred at the degraded site. This was explained by the higher sediment availability and the higher average wind speeds at the dune site. For all events, the range in mass transport (difference between minimum and maximum mass transport) was large in comparison to the mean (Table 3), indicating that mass transport is variable in space. This large spatial variability in sediment transport was explained by the spatial variation in the presence of vegetation, mulch coverage and soil crusts. These parameters have a large influence on the transport capacity of the wind and the erodibility of the soil (Hagen, 1996a; Molion and Moore, 1983a,b; Rice et al., 1997).

3.1. Revised wind erosion equation

Fryrear et al. (1998a) and Zobeck et al. (2001) performed a validation of RWEQ over a wide range of soil types and climates in the USA. They found correlations between observed and predicted Q_{max} of 0.82 (Fryrear et al., 1998a) and 0.70 (Zobeck et al., 2001) though no correlation between measured and predicted s values was observed. This suggests that RWEQ predicts only Q_{max} well under soil and climate conditions for which RWEQ was initially developed and s is poorly predicted in these circumstances.

Since RWEQ is an empirical based model, the model can only be used with input parameters, which fall inside the test range of the model. In the RWEQ manual only for Eqs. (2) (EF) and (3) (SCF) are test ranges given (Table 1) (Fryrear et al., 1998b). Tables 1 and 2 show that all input parameters of the sites fall within the validation range of the formulas, with the exception of the organic matter of the dune, which is low. Further, RWEQ is supposed to be applicable throughout the USA and so for a wide range of climates. Convective wind erosion events comparable with the convective storms in the Sahel do occur in the USA (e.g. Dogget et al., 2003). Therefore, it is assumed that atmospheric conditions during a Sahelian wind erosion event will fall inside the test range of RWEQ. Since almost all input parameters fall inside the test range, it is assumed that Eqs. (4) (Q_{max}) and (5) (s) are also valid for the Sahelian situation.

Initially it was intended to incorporate the spatial variation in the input parameters of RWEQ, for simulation of wind erosion in the Katchari catchment. However, due to the structure of Eqs. (1) and (9) ($Q(x)$ depends on Q_{max} and s), this became difficult. With a spatial variable s, it is difficult to determine x and so $Q(x)$ (Fig. 1(a),(b)). Therefore, to determine Q_{maxp} and s_p, initially no spatial variation in the input parameters was taken into account. Average field values for all input parameters were used. Furthermore, the influence of scattered vegetation and topography were not taken into account because these parameters were not included in the model. These influences should not have had any effect on the predictions at the degraded site, but scattered vegetation surely acted on mass transport at the valley. So for the valley site, an overestimation of mass transport was expected.

Table 4 shows the results of RWEQ model simulations in the Katchari catchment. At the dune, s_p values are generally underestimated with an average of 7.4%

Table 4
Modelling results of RWEQ compared with field measurements of maximum mass transport (Q_{max}) and critical field length (s) for 11 wind erosion events at three research plots in the Katchari catchment in Burkina Faso. Subscript m, measured; subscript p, predicted; −, no measurements available

Date	Degraded Site				Valley				Dune			
	Q_{maxm} (kg/m)	Q_{maxp} (kg/m)	s_m (m)	s_p (m)	Q_{maxm} (kg/m)	Q_{maxp} (kg/m)	s_m (m)	s_p (m)	Q_{maxm} (kg/m)	Q_{maxp} (kg/m)	s_m (m)	s_p (m)
20 May	–	–	–	–	41.7	20.6	912.3	1004.5	49.4	43.4	1059.7	978.8
22 May	34.9	5.5	2102.8	1875.8	253.7	22.7	1280.3	1125.7	204.7	30.0	1090.1	1014.3
3 June	5.7	13	1364.6	1402.1	18.0	11.9	760.5	844.9	123.4	66.1	829.5	790.4
9 June	13.2	10.9	1936.7	2169.9	42.4	42.4	1309.4	1309	215.9	90.6	1600.4	1557.4
12 June	12.3	3.9	2537.2	2371.2	241.2	9.9	1378.6	1679	56.8	13.5	1592.5	1466.4
19 June	51.8	11.1	1419.5	1621.6	294.0	42.7	1566.7	980.3	417.8	56.5	932.4	883.5
22 June	52.2	4.26	2470.4	2300.8	138.3	11.9	1280.8	1221.8	196.3	28.7	2699.4	2561.5
29 June	40.0	0.0	1279.7	1968.7	48.9	9.8	1195.1	1026.9	468.1	23.7	1255.9	1145.8
3 July	238	9.3	1586.2	1588.3	46.9	27.6	562	797.5	485.5	37.1	206.3	715.0
10 July	90.7	3.6	1545	1374	163.9	14.1	891.9	828.1	52.2	52.2	1189.0	1204.2
11 July	20.3	8.1	1476.3	1672.6	15.5	7.8	1699.9	1687.9	683.3	3.1	2853.8	2940.3
13 July	30.4	1.7	3562.2	3962	95.3	6.8	2564.5	2387.5	60.2	10.5	4639.0	5111.9

from the s_m values, with one over-prediction of 246% for the event of 3 July. For the valley, s_p values are generally underestimated with 13.9% and for the degraded site with 12.9%.

For the dune site, Q_{maxp} was generally underestimated with an average of 68.3%, at the valley site with 66.9% and at the degraded site with 79.9%. So RWEQ gave acceptable predictions of the s_p values; though failed to predict $Q_{maxp.}$ With a poor prediction of Q_{maxp}, a good prediction of s_p is not very meaningful. It is no use to know where a maximum mass transport might occur, knowing that predictions of this amount are inaccurate. Furthermore, due to the poor prediction of Q_{maxp}, $Q(x)_p$ cannot be expected to be well predicted. Fig. 4 shows the measured and predicted mass fluxes ($Q(x)$ in kg/m) at the valley at 13 July 2001, with $Q_{maxp} = 6.8$ kg/m, $\alpha = 1994.35$ and $s_p = 2387.5$ (Table 4). From Fig. 4, it is clear that $Q(x)$ is highly under predicted. The apparent inability of the model to predict spatial variation in mass transport can here be explained by the fact that average field values were used for determination of Q_{maxp} and s_p. Were the field average Q_{maxp} and Q_{maxm} in the same order of magnitude, this could be overcome by pursuing the following procedure. First calculate $Q(x)_p$ based on the average field values, then determine the specific Q_{maxp} and s_p for that point and multiply $Q(x)_p$ by a factor based on the relation between the average field value for Q_{maxp} and the specific point value for $Q_{maxp.}$ However, the field average Q_{maxp} was not in the same order of magnitude as the field average Q_{maxm}, so this procedure could not lead to better results.

At our sites, the random roughness was very low (roughness values measured with the chain method (Saleh, 1993) ranged from 0.93 at the degraded site to 4.5 at the valley floor) and no oriented roughness (caused by cultivation) was present. Therefore, the parameter K' had hardly any influence on the prediction of Q_{maxp} and s_p. The same accounts for the parameter COG; average soil cover by dead and living crops ranged from 0% to 5% for all sites. So at our sites, the weather factor (WF), the crust factor (SCF) and the erodible fraction (EF) were the most important factors in determining Q_{maxp} and s_p. Saltiphone data were used to make sure that the wind factor, and therefore the WF, were correctly predicted. Soil wetness was very low (<5%) and had no influence on the WF. Despite high wind speeds, low values for maximum mass transport were predicted. Apparently, the model predicted transport to be sediment limited and only the EF and the SCF, calculated with Eqs. (2) and (3), could have caused the low prediction of Q_{maxp}. Both the EF and the SCF were calculated based on textural characteristics of the soil. In the Sahel, crust development is apart from textural characteristics determined by rainfall kinetic energy and topography. Furthermore, crust type highly influence sediment availability. The equations for EF and SCF do not represent the Sahelian situation and modifications should be considered.

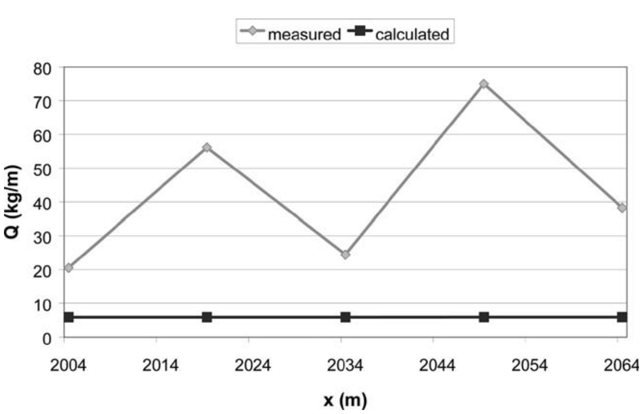

Fig. 4. Measured and RWEQ predicted mass transport for an event at the valley, 13 July 2001, Katchari catchment Burkina Faso. $\alpha = 1994.35$ m.

Even though the Sahelian soils are prone to crusting, it is clear from the field measurements that sediment was available for transport. In RWEQ, the erodible fraction (EF) seems to be the most limiting factor for a correct prediction of Q_{maxp} (EF dune, 0.66; EF valley, 0.53 and EF degraded, 0.43). A possible explanation for these low values is that crust type (sediment availability) and abrasion of the crust by saltating particles are not taken into account in the prediction of EF.

Parameters, which might be considered to be used for determination of the soil crust factor (SCF) (SCF dune, 0.94; SCF valley, 0.85 and SCF degraded, 0.24) are topography and rainfall intensity and amount since last tillage. With these parameters, it might be possible to predict the spatial distribution of crust type and strength, which could then be used to modify the prediction of EF.

Apart from the weak performances of RWEQ in determining Q_{maxp}, the model has some constraints because of its structure. First of all, it assumes a non-eroding boundary around the field, which is hardly ever present in the Sahel. We tried to circumvent this boundary condition by the introduction of α in Eq. (9). However, this equation needs to be tested to determine if its use is justified. Furthermore, the model assumes a more or less homogeneous field for soil management, soil crusting, and vegetation cover. Only the distance from the non-eroding boundary determines variation in mass transport over the field. In the Sahel, the fields are seldom homogeneous for the above-described parameters. Therefore, the model structure should be drastically changed before it can be applied in the Sahel. For the RWEQ in its current state, we see no future application to traditionally cultivated fields in the Sahel.

3.2. WEPS

The WEPS erosion sub-model was tested both inside the USA (Hagen, 2001; Van Donk and Skidmore, 2001) and outside the USA (Funk et al., 2002). The results for total soil loss for an event and the temporal changes in transport capacity were considered satisfying by the authors.

The wind field could be assumed non-disturbed for the events of 9 June and 11 and 13 July since the wind came from northeast (Table 3). Both the degraded site and the Windou-bare site had no vegetation cover and no oriented roughness caused by cultivation practices. So according to WEPS, the roughness length ($Z0_p$) for these sites is only determined by the random roughness. The sites Windou-mulch and Sadore had a mulch cover of approximately 5%. Furthermore, at Windou-mulch, a small crop with a height of 20 cm was present during the event of 13 July 2002.

Table 5 presents the values for measured U^*_m and $Z0_m$ and predicted U^*_p and $Z0_p$. As can be seen in this table, $Z0_p$ and U^*_{p1} are only well predicted for Sadore. For all other sites, $Z0_p$ is highly under estimated and so is U^*_{p1}. A possible explanation is that around both the degraded site and the sites in Windou natural vegetation was present.

Even though we tried to set up the measurement equipment so that obstacles did not directly hamper the measured wind profile, it was possible that the scattered vegetation in the area influenced the wind field and increased $Z0_m$. Wolfe and Nickling (1993) state that in sparsely vegetated areas, a logarithmic wind profile may exist, but that the effect of individual roughness elements should be considered. Vegetation interacts with the mean flow of wind by extracting momentum from the wind; producing turbulence and breaking down large scale, turbulent eddies into smaller scale motions, this might result in a larger $Z0_m$.

Since WEPS only accounts for uniform vegetation and does not take the effect of the scattered vegetation within and around the research site into account, the model was run with $Z0_m$ as an input parameter.

In order to determine the time of initiation and cessation of sediment transport, we used U^*_{p2} for the ratio between shear velocity and the threshold shear velocity ($U^*_p(t)$/Wust) for the degraded site and the Windou sites. For the Sadore site, we used U^*_{p1}. After the first calculations, WEPS appeared to be extremely sensitive to soil wetness. Even at the sandy soils of Windou-bare with low water content ($<5\%$) in the top 2 cm soil, the ratio $U^*_p(t)$/Wust was smaller than 1 for all events, so no mass transport could occur. From field observations, it was clear that soil wetness was not a limiting factor for wind erosion, so we set the input parameter soil wetness to 0 for all events at all sites. Then WEPS estimated time of initiation and cessation of mass transport very well for the Sadore and Windou sites. Fig. 5(A) shows the ratio $U^*_p(t)$/Wust and the saltiphone data for the event of July 3, 1993 at the Sadore site. It is clear that as soon as $U^*_p(t)$/Wust becomes larger than 1, saltation transport is recorded and as soon as the ratio drops below 1 transport is no longer registered. For the degraded site, WEPS rarely predicted ratios larger than 1 (Fig. 5(b)). This is reasonable taking the soil surface conditions at the degraded site into account (a crusted soil with gravel embedded and on top of the crust). However, the saltiphone did record some saltation transport. Therefore, the threshold for transport (Wusp) and the ratio $U^*_p(t)$/Wusp were calculated. Fig. 5(b) shows both

Table 5
Values for measured (m) (using a wind profile) and predicted (p) (by WEPS in PCRaster) roughness length (Z0) and friction velocity (U^*) for four research sites, Sadore in Niger, Degraded site in the Katchari catchment, Burkina Faso and Windou-bare and Windou-mulch in the Windou catchment in Burkina Faso

Site	Date	$Z0_m$ (mm)	$Z0_p$ (mm)	U^*_m (m/s)	U^*_{p1} (m/s)	U^*_{p2} (m/s)
Sadore	26 June 1993	0.2	0.56	0.45	0.37	–
	30 June 1993	7.0	0.56	0.50	0.43	–
	3 July 1993	0.5	0.56	0.54	0.48	–
Degraded site	9 June 2001	2.15	0.36	0.51	0.40	0.50
	11 July 2001	3.78	0.36	0.52	0.38	0.52
	13 July 2001	4.82	0.36	0.53	0.37	0.53
Windou-bare	3 June 2002	5.41	0.19	0.58	0.38	0.59
	13 July 2002	8.80	0.265	0.73	0.45	0.74
Windou-mulch	3 June 2002	0.65	0.36	0.46	0.36	0.46
	14 June 2002	1.47	0.36	0.50	0.36	0.50
	13 July 2002	1.74	0.44	0.54	0.44	0.54

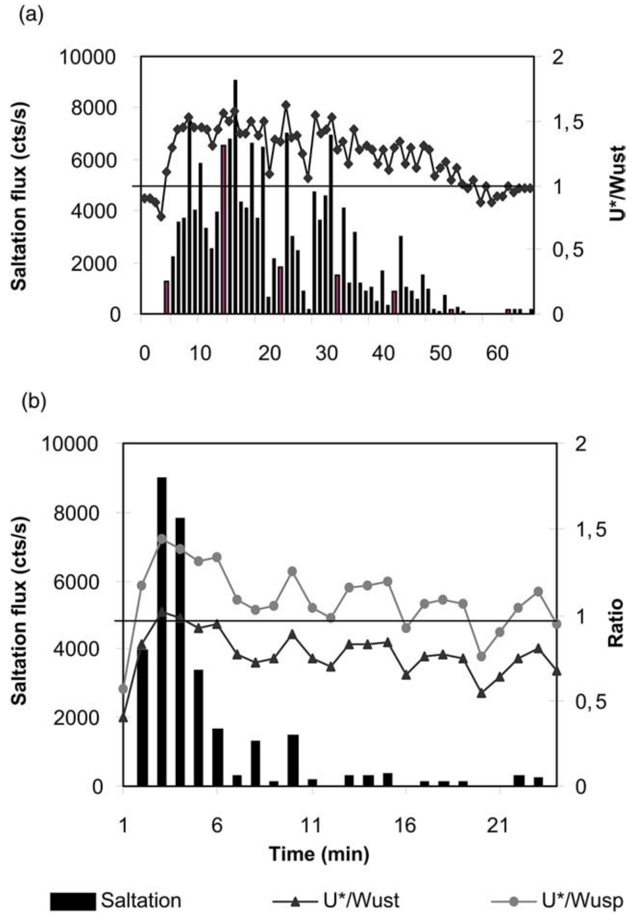

Fig. 5. (a) Measured saltation flux versus ratio of the friction velocity (U^*) and the threshold friction velocity for entrainment (Wust) as predicted by WEPS for a wind erosion event at 3 July 1993, Sadore, Niger. (b) Measured saltation flux versus ratio of the friction velocity (U^*) and threshold friction velocity for entrainment (Wust) and the ratio of the friction velocity (U^*) and the threshold friction velocity for transport (Wusp) for a wind erosion event at 9 July 2001, at the degraded site, Katchari catchment, Burkina Faso.

ratios ($U_p^*(t)$/Wust and $U_p^*(t)$/Wusp) and measured saltation transport for the wind erosion event at 9 June 2001 at the degraded site. The ratio $U_p^*(t)$/Wust is only once larger than 1, but at moments saltation transport was registered with the saltiphone, the ratio $U_p^*(t)$/Wust was indeed larger than 1. Apparently, the measured saltation fluxes derived from sediment input to the research site.

The mass transport by wind was simulated with WEPS in PCRaster for the research sites at the dune, the valley floor, and the degraded site. The roughness length ($Z0_m$), calculated from the measured wind profile at the degraded site, was used to predict U_p^* using Eq. (6). Eq. (7) was used to predict U_p^* at the dune and the valley. Figs. 6–8 show the main input maps and the maps of predicted mass transport for the event of 11 July at the dune, the valley and the degraded site, respectively.

Comparing the maps of crop coverage, roughness and crust type at the dune with the map with predicted mass transport (Fig. 6), it becomes clear that here crop coverage is the most important wind erosion controlling parameter. Large amounts of mass transport are predicted at bare areas. The higher vegetation coverage combined with the lack of transportable sediment on the erosion crust results in lower mass transport rates at the south-western part of the field. Though sediment input is high, the amount of mass transport is in the same order of magnitude and the pattern of erosion and deposition agrees reasonably well with the measured pattern. Only the highest peak of sediment transport is predicted too early over the transect. A possible explanation for this is that the vegetation map is created with inversed distance interpolation based on 15×5 measurement points. Making aerial pictures with kite-photography and digitising these photos might be a more precise procedure for obtaining maps with vegetation coverage.

Due to a lack of crop cover and the presence of a combined structural/erosion crust, large amounts of mass transport are predicted and measured at the north-eastern part of the valley (Fig. 7). The low mass transport values in the north-western part of the field are explained by the presence of an erosion crust and so a lack of transportable sediment. Though not measured, a large decline in mass transport was predicted in the centre of the field. This can be explained by the presence of an area of approximately 8×8 m with a dense mulch cover. Due to the interpolation technique the input map with vegetation cover was not correct. This emphasises the importance of reliable information of the distribution of the input parameters.

Due to the lack of vegetation, mass transport at the degraded site is only determined by the distribution of the crust types (Fig. 8). The moment wind-blown sediment arrives at the gravel crust, the sediment is entrapped by the loose gravel. Behind the gravel crust erosion occurs. The predicted large amounts of mass transport over the structural crust were not measured. A possible explanation for this is that WEPS initially assumes that the loose material at the crust has the same size distribution as the soil under the crust. However, here, the loose material on top of the crust is merely a lag deposit of rough sand (Fig. 9), which will generally be transported in creep mode. Here, it might have been better to use the size distribution of the loose material on top of the crust as an input parameter.

4. Conclusion

After testing the RWEQ and the WEPS on their spatial predictions of wind-blown mass transport at three geomorphic units in the Katchari catchment in

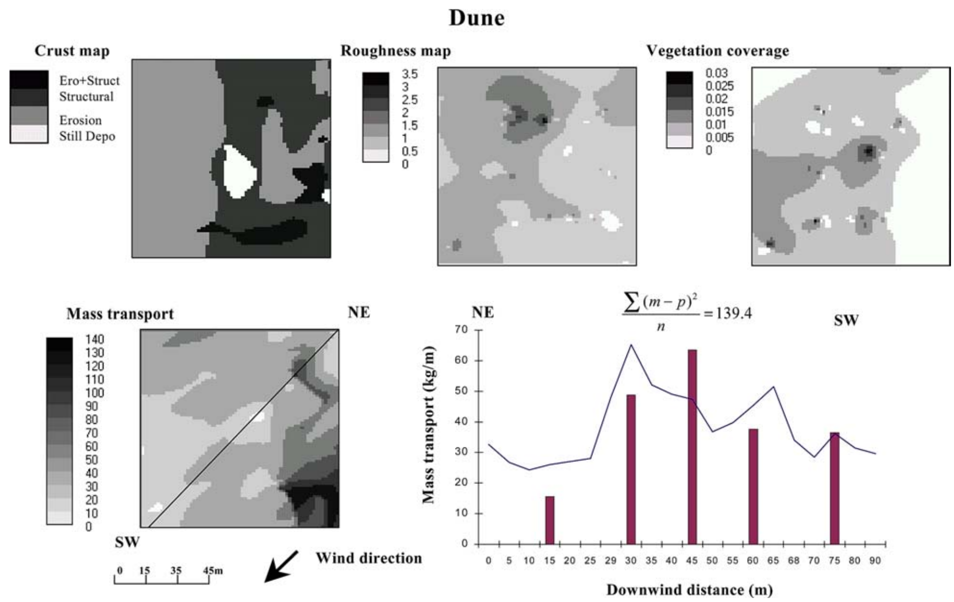

Fig. 6. Distribution of the crust types, roughness, vegetation cover and predicted mass transport and transect of predicted and measured mass transport for the wind erosion event of 11 July 2001 at the dune in the Katchari catchment. The black line indicates the position of the transect. The transect should be read along the wind direction, positive gradients indicating erosion, negative gradients indicating deposition. Ero+struct, combined erosion and structural crust; structural, structural crust; erosion, erosion crust; Still Depo, still depositional crust (Valentin and Bresson, 1992).

northern Burkina Faso, it was concluded that RWEQ is not suitable and WEPS in PCRaster is suitable for application in the Sahel.

RWEQ gave a good estimation of the critical field length (s_p) but poorly predicted maximum mass transport (Q_{maxp}). Furthermore, due to the poor prediction of Q_{maxp}, $Q(x)_p$, which depends strongly on Q_{maxp} and s_p, was also under-predicted. At our site, little soil cover by dead or living vegetation was present. Hence the most important factors in determining Q_{maxp} were the

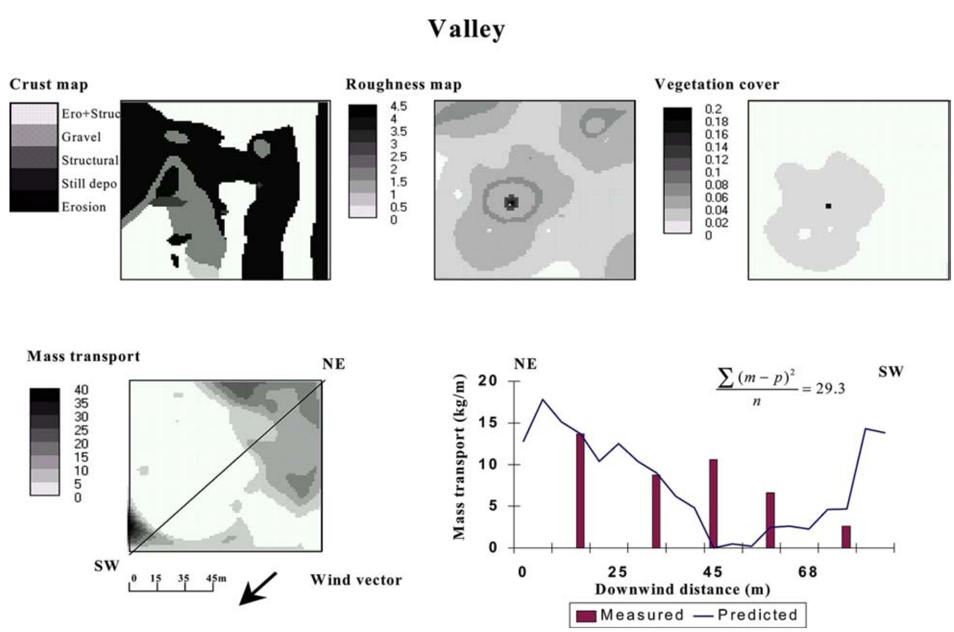

Fig. 7. Distribution of the crust types, roughness, vegetation cover and predicted mass transport and transect of predicted and measured mass transport for the wind erosion event of 11 July 2001 at the valley in the Katchari catchment. The black line indicates the position of the transect. The transect should be read along the wind direction, positive gradients indicating erosion, negative gradients indicating deposition. Ero+struct, combined erosion and structural crust; structural, structural crust; erosion, erosion crust; Still Depo, still depositional crust (Valentin and Bresson, 1992).

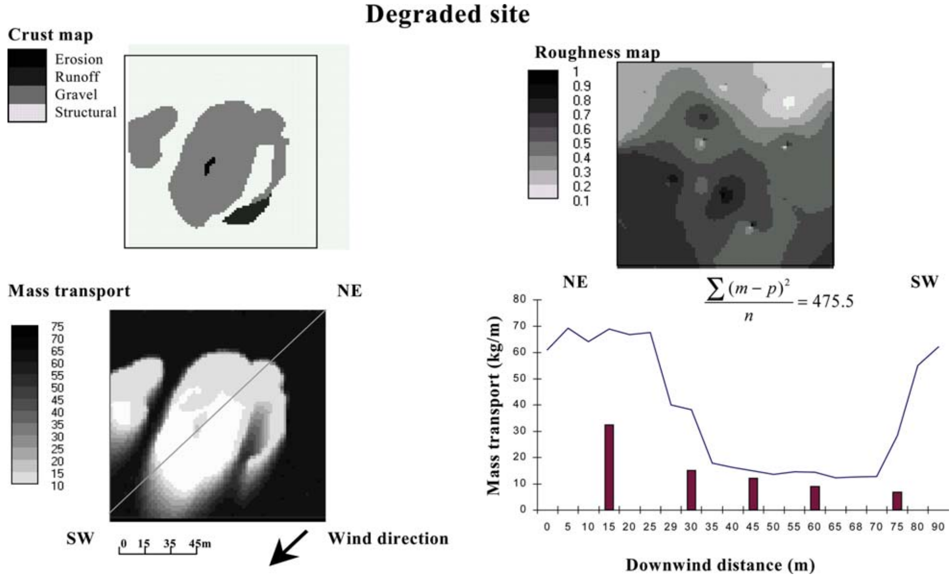

Fig. 8. Distribution of the crust types, roughness, vegetation cover and predicted mass transport and transect of predicted and measured mass transport for the wind erosion event of 11 July 2001 at the degraded in the Katchari catchment. The black line indicates the position of the transect. The transect should be read along the wind direction, positive gradients indicating erosion, negative gradients indicating deposition. Erosion, erosion crust; runoff, runoff depositional crust; gravel, gravel crust; structural, structural crust (Valentin and Bresson, 1992).

crust factor (SCF) and the erodible fraction (EF). For successful application of RWEQ in the Sahel, it appears necessary to adjust the formulas calculating SCF and EF. In addition, the structure of RWEQ may limit its successful application. First of all, the required non-eroding boundary is seldom present at Sahelian fields. Application of Eq. (9) might circumvent this problem. However, there are still uncertainties about Eq. (9) because this formula is not yet tested. RWEQ further assumes a field that is more or less homogeneous for vegetation cover, management and roughness. But such fields are seldom found in the Sahel. Therefore, despite some good results in the USA, it is concluded that RWEQ as it is, is not suitable for application in a Sahelian environment.

WEPS gave a good estimation of the roughness length on a non-cultivated field without natural vegetation and low mulch cover. For fields with natural vegetation at and around the research plot, the roughness length was underestimated. But when provided a good estimate for the roughness length, WEPS gave, in all cases, a good estimation of the friction velocity and correctly predicted time of initiation and cessation of transport assuming a dry soil surface (Fig. 5). Furthermore, the model gave an acceptable prediction of the spatial distribution of mass transport

Fig. 9. Combined structural and erosion crust at the degraded site.

at the research sites. Therefore, it is concluded that WEPS in PCRaster is suitable for prediction of wind erosion in a Sahelian environment. To obtain even better predictions, the effect of sparse, scattered vegetation should be included in the model. A constraint for using WEPS in the Sahel is that WEPS predictions of spatial variation in sediment transport is closely linked to the spatial variation in the input parameters. Therefore, one needs accurate estimations of the spatial variation of all input parameters, and this might be an expensive assignment.

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