Nutrient losses by wind and water, measurements and modelling

Catena

Visser, S.M.; Stroosnijder, L.; Chardon, W.J.

https://doi.org/10.1016/j.catena.2005.07.003

Available online at www.sciencedirect.com
SCIENCE DIRECT®

ELSEVIER

Catena 63 (2005) 1–22

CATENA

www.elsevier.com/locate/catena

Nutrient losses by wind and water, measurements and modelling

S.M. Visser [a,*], L. Stroosnijder [a], W.J. Chardon [b]

[a] Department of Environmental Sciences, Erosion and Soil and Water Conservation Group, Wageningen University. Nieuwe Kanaal 11, 6908 PA Wageningen, Netherlands
[b] Alterra, Wageningen UR, Soil Science Centre, PO Box 47, 6700AA, Wageningen, The Netherlands

Received 23 January 2004; received in revised form 4 July 2005; accepted 22 July 2005

Abstract

In the Sahelian zone of West-Africa, erosion by both wind and water causes a serious decline in fertility of the already low fertile soils. Despite the fact that the flow of nutrients has been intensively investigated by the use of nutrient balances, little attention has been paid to the contribution of the soil erosion to the nutrient balance.

Two physically based models (WEPS and EUROSEM, both written in PCRaster) were extended with nutrient modules to investigate the role of wind and water erosion in the loss and gain of nutrients at the scale of a Sahelian field. The models are applied at three geomorphic units in the Katchari catchment in northern Burkina Faso.

WEPS can predict spatial patterns of erosion and deposition due to wind-blown particle transport. Depending on wind direction, crusting and vegetation cover net erosion or deposition can occur. When erosion occurs considerable amounts of nutrients are lost, but when deposition occurs, most of these nutrients may be regained. Soil loss by water erosion is closely related to the crust type present, which regulates infiltration and thus runoff. Nutrient losses by water erosion are small compared with those by wind erosion, but are forever lost for the area. Sediment transport by wind in saltation mode results in the largest soil and nutrient loss at the time scale of an event.

Keywords: Nutrients; Wind erosion; Water erosion; Modelling

* Corresponding author. Tel.: +31 317 484583; fax: +31 317 486103.
E-mail address: Saskia.Faye-Visser@wur.nl (S.M. Visser).

0341-8162/$ - see front matter
doi:10.1016/j.catena.2005.07.003

1. Introduction

Ever since the 1960s, rainfall in the Sahel has shown a general decline. From the 1980s on, rainfall dropped under the long-term average for most of Africa, a trend that continued through the 1990s (Nicoleson, 2001). 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 drought and overexploitation has resulted in large-scale land degradation. According to Williams and Balling (1994) 332 million hectares of the African drylands are subjected to soil degradation. The land degradation process include: erosion by both wind and water and deposition elsewhere, long-term reduction in the amount and diversity of natural vegetation, and salinisation of soils (Dregne et al., 1991).

Especially for the already low fertile soils of the semi-arid tropics of West Africa, soil erosion is a major threat to sustainable use of soil and water resources. Lal (1998) indicated that low levels of N, P, K and low cation exchange capacity (CEC) are among the most important chemical and nutritional constraints for crop growth and are accentuated by soil erosion. Since the fine particle fraction is often preferentially eroded, a disproportionate loss of the soil nutrients can occur, leading to even greater degradation (Hashim et al., 1998).

In the Sahel, severe wind and water erosion mainly occurs in the first half of the rainy season (May–July). In this period rainfall occurs in high intensity thunderstorms often preceded by violent winds. During this period the soils are at its barest and vulnerable for erosion. The already poor soils lose their fertile topsoil due to sediment transported by wind, which covers creep, saltation and suspension (Bagnold, 1941), and by water due to dissolved transport of nutrients and sediment transported by runoff, which covers all forms of transport, including bedload (Stroosnijder, 1995).

Despite the fact that the flow of nutrients in sub-Saharan African agriculture has been intensively investigated by the use of nutrient balances (De Jager et al., 1998; Nandwa and Bekunda, 1998; Wortmann and Kaizzi, 1998), little attention has been paid to the contribution of soil erosion to the nutrient balance of this area. Nutrient losses due to soil erosion are often calculated based on average soil losses per hectare and precise measurements of nutrient contents of the eroded sediment are not often performed in the Sahel.

Nutrient losses by wind erosion in the Sahel are so far only quantified by Bielders et al. (2002) and Sterk et al. (1996). During their research at a pearl-millet plot in southwest Niger Sterk et al. (1996) found that total element (TE) content of wind-blown sediment at 0.05 m was similar to those of the topsoil, but at 0.5 m the sediment was approximately three times more enriched than the topsoil. Furthermore, they showed that the main mass of nutrients is transported by saltation transport, despite the fact that suspended sediment is much more enriched in nutrients. Sterk et al. (1996) reported the following TE losses from a 40×60 m experimental plot after two storms: 57.1 kg ha^{-1} K, 79.6 kg ha^{-1} C, 18.3 kg ha^{-1} N and 6.1 kg ha^{-1} P. Bielders et al. (2002) performed measurements on wind-blown sediment transport in a conventionally managed cultivated field and a bush fallow in western Niger. Generally, the nutrient content of the wind-blown sediment declined with distance into the cultivated field and increased with distance into the bush fallow. A net deposition of nutrients was measured in the bush fallow and a net loss of nutrients occurred at the cultivated field. For both researches stands that nutrient losses, although low in absolute terms, were high compared to the average nutrient uptake by a millet crop (Buerkert, 1995).

As for wind erosion, not much research has been performed on the loss of nutrients by water erosion in the Sahel. Geelhoed (1995) investigated the losses of nutrients by water erosion on 1 m^2 runoff plots in Burkina Faso. He calculated annual losses of 654 kg C ha^{-1}, 51 kg N ha^{-1} and 8.7 kg P ha^{-1}, concluding that due to the large nutrient enrichment ratios in the eroded sediment nutrient losses are large. Furthermore, large amounts of soluble N were lost in the runoff water. Ribolzi et al. (2003) showed that not only runoff water but also subsurface flow transports large amounts of solutes. The results of Geelhoed (1995) agree with the results of Cogle et al. (2002) found for an Alfisol in the semi-arid tropics of India, indicating that despite low values for total soil erosion, nutrient losses were large. Due to enrichment ratios larger than 2, annual nutrient losses up to 27 kg N ha^{-1} and 178 kg C ha^{-1} were measured on his 140 m^2 runoff plots.

Thus we can conclude that total nutrient losses due to wind and water erosion are large especially when compared to the annual uptake by a millet crop. However, several researchers argued that at Sahelian fields, soil erosion by wind and water has a large spatial variation (Karambiri et al., 2003; Lal, 1998; Sterk and Stein, 1997; Visser et al., 2003, 2005, in press). From the work of Bielders et al. (2002) we learn that when wind erosion occurs in cultivated fields, the adjacent bush serves as a sink for most of the sediment and therefore also for most of the nutrients. Depending on the local topography this sediment and the nutrients attached can be returned under influence of water erosion, when the fallow is brought back under cultivation. Furthermore, Visser et al. (in press) showed that though large amounts of erosion can be measured at the scale of a runoff plot, total sediment losses from the Sahelian fields can be limited and that merely a redistribution of the sediment, and so the nutrients, occurs. This is confirmed by the knowledge of the local farmers, who can indicate areas of low and high fertility within their fields (Sterk and Haigis, 1998; Visser et al., 2003).

The objective of this study was to evaluate the total effect of wind and water erosion in the loss and gain of nutrients at the scale of a Sahelian field. This will be obtained by the extension of physically based models, suitable for the Sahelian situation, with nutrient modules. Due to the almost simultaneous occurrence of wind and water erosion in the early rainy season in the Sahel, a wind erosion model will be combined with a water erosion model. Both the separate and the total effects of the processes of wind and water erosion at three geomorphic units in the Katchari catchment in northern Burkina Faso will be discussed.

2. Materials and methods

2.1. Field description

During the 2000 and 2001 rainy seasons field experiments on sediment transport by wind and water were conducted in the Katchari catchment in northern Burkina Faso. The

Katchari catchment covers an area of 12 km^2 and is situated in the province Seno, 11 km west of Dori, the provincial capital. In the first half of the rainy season (May–July) severe wind erosion occurs. In this period rainfall occurs in intense thunderstorms that are often preceded by violent winds. Measurements were performed on fields with a different geomorphic setting; a degraded site, a valley site and a dune site.

The degraded site is characterized by its lack of vegetation and a strong gravel crust covering approximately 75% of the soil surface. A well developed erosion crust (Valentin and Bresson, 1992) covers the other 25% of the research plot. The valley is incised by a river, which is dry in the dry season and may flood during the wet season. The research site in the valley is situated approximately 50 m next to the river and is cultivated with millet in the wet season and characterized by a fast development of erosion and still depositional crusts (Valentin and Bresson, 1992). Natural vegetation (trees and bushes) is scattered over the experimental field. Annual herbs are removed by hoeing twice in the wet season. The soil consists of a layer of 25–30 cm of loamy sand on top of a clay loam soil. The loamy sand layer has been trapped with branches by the farmers who wanted to start cultivating this area. The dune site 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 borders of the field at the dune site are demarcated with trees, not forming a continuous row as in a wind barrier. The field is cultivated with millet and annual herbs are removed by hoeing twice a year. The loamy sand soils of this dune complex are prone to crusting, with structural and erosion crusts being the most common (Valentin and Bresson, 1992).

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

2.2. Wind erosion measurements

For the measurement of wind-blown mass transport, each 6400 m^2 research plot was equipped with 17 Modified Wilson and Cooke (MWAC) sediment catchers. Each catcher consists of a vane, which ensures that the catcher always is positioned in the wind direction, and five traps attached on a central pole at heights of 0.05, 0.12, 0.19, 0.26 and 0.75 m. A trap consists of a small (100 ml) PVC sample bottle, closed with a cap through which in- and outlet tubes enter the bottle. The glass tubes have an internal diameter of 8 mm. The trapping efficiency obtained from previous calibration by Sterk and Raats (1996) is defined as the ratio between the measured mass transport rate and the total mass transport rate, and is 0.49. From the weight of the trapped sediment and the duration of the event (measured with a saltiphone), mean horizontal mass fluxes ($q(z)$; kg m^{-2} s^{-1}) at the sampling height z (m) were calculated. A mass flux model was used to describe the relation between horizontal mass flux and height (Sterk and Raats, 1996):

$$q(z) = a(z+1)^{-b} + c\exp\left(-\frac{z}{\beta}\right) \quad (1)$$

where a, b, c and β are regression coefficients. The model describes the vertical profile of horizontal mass flux from the soil surface ($z=0$ m) to any height z.

For each event and each catcher, Eq. (1) was fitted through the measured mass fluxes by non-linear regression (Visser et al., 2004). Here Eq. (1) was only used to describe mass fluxes from 0 to 1 m. Integrating Eq. (1) over height resulted in the mass transport rate Q (kg m^{-1} s^{-1}) at the sampling point. Total mass transport at each sampling point was obtained by correcting for the overall trapping efficiency of the catcher and multiplying with the duration of the event.

An overview of the spatial distribution of measured mass transport was obtained by following a procedure suggested by Sterk and Stein (1997). Event-based maps of sediment transport were obtained by using the variogram from the measurements and applying stochastic simulation, resulting in agreeable results for the degraded and the dune sites. However, the variogram of the valley showed only noise, so the simulated maps bear a low confidence level. A detailed description of this technique and the results can be found in Visser et al. (2004).

To obtain sufficient sediment for nutrient content measurement, the trapped materials of 7 catchers positioned in the northeastern region and of 7 catchers positioned in the southwestern region of the research site were combined. The trapped material was collected at two height ranges; the samples of height range from 0.12 to 0.19 m were grouped and so also the samples of height range from 0.26 to 0.75 m. This resulted in 4 samples per event per site. The representative height of the sample was based on the share of the contents of one trap to the total of the two traps.

A total of fifteen soil samples was taken from the topsoil (0–0.02 m) spread over the experimental field. Five samples were grouped to make one sample, resulting in three soil samples for each research site. For all samples, the total element (TE) contents was determined; nitrogen (N) with the Kjeldahl method and carbon (C) with the Walkley and Black method and total available phosphorus (P) with the Bray II method.

According to Zobeck and Fryrear (1986), the extractable cation content of wind-eroded material as a function of height can be described with a simple power function:

$$X(z) = pz^q \tag{2}$$

where X is the extractable cation content (mg kg^{-1}), z is the height (m) and p and q are (positive) regression coefficients. This equation showed good correlations between fitted and measured extractable cation contents of Na, Ca, Mg, K. Sterk et al. (1996) showed with data of Leys and McTainsh (1994) that Eq. (2) accurately describes the vertical profiles for C (R^2=0.88), N (R^2=0.98) and P (R^2=0.97). Here Eq. (2) was used as a model for the vertical distribution of the TE content with height. Multiplication of Eqs. (1) and (2) results in an equation that describes the vertical profile of TE mass fluxes:

$$f(z) = pz^q \left[a(z+1)^{-b} + c\exp\left(-\frac{z}{\beta} \right) \right] \tag{3}$$

where $f(z)$ is the horizontal mass flux (mg m^{-2} s^{-1}) of a given nutrient at height z (m). The TE mass flux profiles were numerically integrated from z=0 to z=1 m. The total TE mass transport M_t (mg m^{-1}) was obtained by correcting measured TE mass transport rates for the trapping efficiency and multiplying with the event duration. Average TE content of the transported sediment (mg kg^{-1}) was obtained by dividing the total TE mass transport (mg m^{-1}) by the total sediment transport (kg m^{-1}).

By calculating the ratio of the content of a particular element in the transported material to the content of the element that is in the parent soil, average enrichment ratio's (ER) for each site were obtained. These ER were used as input for the wind erosion model.

2.3. Wind erosion modelling

Visser et al. (2005) rewrote the erosion sub-model of the Wind Erosion Prediction System (WEPS) (Hagen, 1996) in the dynamic modelling language PCRaster (De Jong, 1997). WEPS is a process-based daily time step computer model that predicts soil erosion through simulation of the physical processes that control wind erosion (Hagen, 1991).Translating the original WEPS code to PCRaster allows us to insert wind erosion controlling parameters with a spatial variation, e.g., vegetation cover, crust type, and soil roughness. The model calculates the friction velocities and the threshold friction velocities for each grid cell. When the friction velocity is larger than the threshold friction velocity sediment transport is possible, and the model calculates soil loss or deposition for each grid cell and updates the surface parameters. The original erosion sub-model of WEPS was adapted for the Sahel by:

1) Allowing sediment to enter the field (no non-eroding boundaries (Visser et al., 2005)),
2) Allowing transport to occur when erosion is no longer possible (friction velocity is still larger than transport threshold but smaller than the erosion threshold due to the small grid size),
3) Assuming the water content of the topsoil to be 0 (Visser et al., 2005).

For a detailed description of the WEPS erosion sub-model and the adaptations made for the Sahelian environment see Hagen (1996) and Visser et al. (2005). For this research the WEPS in PCRaster model is extended with a nutrient module. Nutrient losses were calculated by:

$$\mathrm{EGN} = \mathrm{EG}^{*}N_{\mathrm{soil}}{}^{*}\mathrm{ERN} \qquad (4)$$

where: EGN is total loss (negative) or gain (positive) in nutrients (mg); EG is loss (negative) or gain (positive) of saltation sediment (kg); N_{soil} is nutrient content of topsoil (mg kg^{-1}), and ERN; the height integrated average enrichment ratio for a specific nutrient. This equation was added to calculate the redistribution of nitrogen, phosphorus and carbon.

2.4. Water erosion measurements

During the rainy season of 2000 and 2001 field data of water erosion events were collected at the three sites in the Katchari catchment. The degraded site and the dune site were equipped with a complete weather station continuously measuring wind speed (at 0.5, 1, 2 and 3 m) and direction, temperature, total rainfall, soil moisture content (at a depth of approximately 5 cm) and total solar energy. During the 2001 rainy season the valley site was equipped with an automatic rain gauge, which measured rainfall amounts at one-minute intervals. At each site three runoff plots were installed; one with an area of 1 m^2 (1×1 m) and two with an area of 20 m^2 (10 m length, 2 m width). Each plot was closed at its upstream boundary so that run-on was not possible. Under the 1-m^2 plots an automatic tipping bucket was installed, which recorded overland-flow intensity at one-minute intervals. Overland flow and sediment load from the 20-m^2 plots were captured in four oil-barrels at the end of the plot. After a rainfall event total collected overland flow was measured with a precision of 0.5 l. All water and sediment of the first two oil barrels were deposed into two large buckets and left for 48 h so that resettlement of sediment in suspension could occur. Then the water was poured and the sediment was collected, dried and weighed. The N, C and P contents of the eroded sediment were determined using the same method as described for wind erosion and the enrichment ratios were calculated. These ER were used as input for the water erosion model. To determine the nutrient content in runoff water (μg l^{-1}), two 1-l sample bottles were filled with the runoff water from the first oil barrel before measuring total overland flow.

2.5. Water erosion modelling

Visser et al. (in press) extended the PCRaster version of EUROSEM (Van Dijck and Karssenberg, 2000) with the erosion and sediment transport modules of EUROSEM (Morgan et al., 1998). EUROSEM was developed as an event-based model designed to operate for successive short time steps. EUROSEM models the interception of water by the vegetation cover, the volume of rainfall that reaches the soil as direct through fall and leaf drainage, infiltration, the volume of depression storage, the detachment of soil by rainfall and runoff, transport capacity of flow and deposition of sediment. Runoff discharge is calculated using the kinematic wave equation, routed over the soil surface using a LDD (local drain direction map) and soil loss is computed as a sediment discharge, defined as the product of the volume of overland flow and the sediment concentration passing a certain point at a given time.

The extended version of EUROSEM in PCRaster was adapted at four points to become applicable to the Sahelian situation by:

1) Simulating wind driven rainfall,
2) Simulating infiltration with a one layer Green and Ampt infiltration model, using an effective infiltration capacity (K_e) for the combined crust and underlying soil,
3) Assuming that overland flow only occurs in the form of turbulent sheet flow, with rainfall falling in the flow causing additional transport capacity,
4) Allowing pool formation, which occurs due to the small height changes in the local topography.

For a detailed description of EUROSEM and the version of EUROSEM adapted to the Sahelian environment the reader is referred to Morgan et al. (1992), Morgan et al. (1998) and Visser et al. (in press). For this research the EUROSEM in PCRaster model is further extended with a nutrient module. The amount of soluble nutrient loss was computed based on the measured nutrient content in the runoff water (μg l^{-1}) multiplied with the simulated discharge at the field outlets (l s^{-1}). Loss of soluble nutrients by leaching was not measured and thus is not accounted for in the model. The solid nutrient loss is simulated by first multiplying the detached sediment (kg) (either detached by flow or by rainfall) with the nutrient content of the soil and the ER for each nutrient. Finally, total nutrient losses are computed as a nutrient discharge, defined as the product of the volume of overland flow and the nutrient concentration in the flow passing a certain point in a given time period.

2.6. Combination of the wind and water erosion model

In order to be able to simulate a wind erosion event that is directly followed by intense rainfall, several assumptions had to be made. First of all it is assumed that as soon as rainfall starts all airborne material in the transport mode is directly deposed in the grid cell where it is present at that time-step. Furthermore, erosion by wind is no longer possible from this moment on due to the wetness of the soil surface.

Secondly, splash transport was not considered (only detachment by splash). The authors are aware of the fact that this may lead to an underestimation of erosion and deposition in the field. However, more research on this subject in Sahelian fields (both on flat and sloping fields) is necessary in order to completely understand this process.

Finally, it is assumed that the nutrient content of the soil is initially distributed homogeneously (at least for the top centimetres) and that the material that is deposed under wind-driven circumstances is enriched with nutrients. In other words, at places where erosion occurred it is assumed that the soil contains its initial concentration of nutrients and at places where deposition occurred the topsoil is enriched with nutrients. These assumptions result in a homogeneous distribution of nutrient concentration at the onset of wind-blown mass transport and a non-homogeneous distribution of nutrient concentration over the field at the onset of rainfall.

So far the wind erosion model uses input maps with different map attributes (X_{min} Y_{min}, X_{max} Y_{max}) and simulates with a larger time-step than the water erosion model. Therefore, first the wind erosion model is run, then the input maps for the water model are created and finally the water erosion model is run.

3. Results and discussion

During the 2001 rainy season several wind erosion events, resulting in intense mass transport, occurred. Some of these events were followed by rainfall. For three events that were not followed by rainfall the nutrient content of the wind-blown sediment was determined. The events of 9 June, 22 June and 3 July 2001(Table 1) will be used for the simulation of nutrient transport by wind alone.

During both the 2000 and the 2001 rainy season intense rainfall events occurred resulting in severe erosion. However most of the early events were preceded by several minutes of wind-blown sediment transport and the measured sediment in the runoff plots

Table 1
Duration (D), wind direction (Dir), average wind speed (WS) at 2 m, average wind-blown mass transport (Q) and range of measured wind-blown mass transport for 4 wind erosion events

Wind erosion	Dune					Degraded					Valley*	
	D (min)	Dir	WS (m s^{-1})	Q (kg m^{-1})	Range (kg m^{-1})	D (min)	Dir	WS (m s^{-1})	Q (kg m^{-1})	Range (kg m^{-1})	Q (kg m^{-1})	Range (kg m^{-1})
Aug 20 2000	10	ESE	13.7	13.1	5.8–52.3	13	ESE	9.7	16.4	4.0–34.7	nm	
June 9 2001	36	NE	8.8	119.1	52.7–206.2	21	ENE	9.3	12.2	5.5–29.8	54.8	19–122.9
June 22 2001	21	E	9.2	100.7	8.1–182.8	19	E	11.8	43.5	2.1–38.4	56.1	5.3–43.1
July 3 2001	20	N	7.4	40.7	8.5–87.7	19	N	7.5	4.6	4.0–34.7	51.0	17.2–84.2

Water erosion	Dune			Degraded			Valley		
	P (mm)	D (min)	*R* (mm)	*P* (mm)	D (min)	*R* (mm)	*P* (mm)	D (min)	*R* (mm)
Aug 20 2000	19.6	50	1.31	18	50	17.9	18	50	0.8
20 July 2001	16	20	7.6	10	16	8.5	10	16	6.8
Aug 15 2001	26.2	194	10.3	28.6	230	18.2	28.6	230	2.9
Aug 20 2001	34.0	65	24.2	27.6	62	24.2	33.8	67	8.3

Total precipitation (*P*), duration (D), and runoff (*R*) for 4 rainfall events at the degraded, dune and valley sites in the Katchari catchment, Burkina Faso. Note that both wind and water erosion occurred on August 20, 2000.
*D, Dir and WS for valley site are the same as for the degraded site.
nm = not measurable.

was a mixture of wind-blown sediment and sediment transported by runoff. To be able to measure the nutrient content of sediment that was only transported by runoff, nutrient content of the sediment of events somewhat later in the season was measured. For the events of 20 July, 15 August and 20 August 2001 (Table 1) we were absolutely sure that no wind-blown mass transport occurred before the event.

During the early rainy season of 2000 wind-blown mass transport was less intense than during the 2001 season. Due to the absence of rainfall in August 2000 young millet plants died and fields were only partly covered by crops. Therefore saltation under influence of the wind was still possible during the event of 20 August 2000. This event will be used for the combined simulation of wind and water erosion. Characteristics of this event can also be found in Table 1.

Texture and nutrient contents of the topsoil are shown in Table 2. P contents are approximately twice the P content found by Bielders et al. (2002), but are very similar to those found by Sterk et al. (1996). The soil studied by Bielders et al. (2002) was a strongly leached, never fertilized sandy soil, whereas the experimental plot studied by Sterk et al. (1996) has probably been enriched in P by fertilisation a couple of years prior to his measurements. This explains the observed differences of the results of this research and the experiment of Sterk et al. (1996) compared to those of Bielders et al. (2002). Organic C content at the dune and the degraded sites are similar to the values found by Bielders et al. (2002) and Sterk et al. (1996). The higher values for organic C at the valley site can be explained by the presence of cattle during the dry season of 2000/2001. Values for N are similar to those found by Bielders et al. (2002) and Sterk et al. (1996).

3.1. Wind erosion measurements

For each MWAC catcher Eq. (1) was fitted through the measured mass fluxes at five heights. Generally the fitted mass flux profiles showed good agreement with the observations (Visser et al., 2004). From the fitted mass flux profiles the total mass fluxes (Qt) were calculated. The range and the average values of all 17 catchers for measured mass transport for each event are given in Table 1.

As a result of variable wind directions no clear trend in TE contents was found. Therefore average ER values for each nutrient for each event were calculated (Tables 3 and 4). ER values used for the event of 20 August 2000 were the average of the measured ER for the three events.

Table 2
Characteristics of the top 2 cm of the soil of the dune, the valley and the degraded site in the Katchari catchment, Burkina Faso

Location	Texture	Sand	Silt	Clay	N	C	P
		%			mg kg^{-1}	mg kg^{-1}	mg kg^{-1}
Dune	Loamy sand	84 (3.5)	13 (3.0)	3 (0.9)	160 (7.1)	1590 (196)	100 (3.2)
Valley	Loamy sand	80 (6.5)	16 (6.2)	5 (0.8)	230 (10.6)	2580 (622)	110 (7.8)
Degraded	Clay loam	59 (1.5)	19 (5.0)	21 (3.7)	300 (49.8)	1820 (238)	170 (4.9)

The standard deviations are shown in brackets.

Table 3
Total nitrogen (N), carbon (C) and phosphorus (P) contents of the materials trapped with the 17 MWAC catchers during three wind erosion events, at three sites in the Katchari catchment

Date	Site	Height (m)	C (mg kg^{-1})	N (mg kg^{-1})	P (mg kg^{-1})
June 9 2001	Dune	0.15	1845	179	57
		0.37	4250	304	80
	Degraded	0.16	3270	252	89
		0.48	5720	298	111
	Valley	0.15	2045	166	47
		0.32	2135	175	55
June 22 2001	Dune	0.15	4365	297	118
		0.44	4385	357	139
	Degraded	0.16	4875	201	103
		0.39	5890	264	128
	Valley	0.15	4090	325	120
		0.4	4720	369	128
July 3 2001	Dune	0.17	3265	308	100
		0.45	4380	327	131
	Degraded	0.16	1920	176	84
		0.41	2950	210	101
	Valley	0.15	3660	253	83
		0.42	4205	284	90

Comparing the ER found in this study with those of Sterk et al. (1996), it is clear that the ER values of phosphorus (P) are very low (even below 1 for the degraded site). This may partly be caused by the presence of iron (Fe) in the soil. Fe binds free P and favours the formation of large aggregates (until 2 mm) and therefore P is not transported by wind. The ER for N and C found in this study agreed well with the ER found by Sterk et al. (1996). Similar to our findings Sterk et al. (1996) found in some cases ER for N <1, though in his research only for the samples from a height of 0.05 m. We do not have an unambiguous explanation for these observations.

Table 4
Enrichment ratios (ER) for nitrogen (N), carbon (C) and phosphorus (P) for four wind erosion events at three sites in the Katchari catchment

Date	Element	ER dune	ER degraded	ER valley
June 9 2001	N	1.48	1.34	0.81
	C	1.32	1.50	0.87
	P	0.62	0.73	0.44
June 22 2001	N	1.91	0.73	1.80
	C	3.04	2.99	1.86
	P	1.30	0.77	1.19
July 3 2001	N	1.92	0.57	1.12
	C	2.51	1.31	1.35
	P	1.15	0.47	0.73
Average values used for August 20 2000	N	1.77	0.88	1.24
	C	2.29	1.93	1.36
	P	1.02	0.66	0.79

3.2. Wind erosion modelling

Visser et al. (2005) showed that the WEPS in PCRaster could predict the pattern of spatial variation in mass transport. However, they did not give a qualitative indication of the reliability of the model results. Therefore, we calculated the correlation coefficients of the maps of simulated mass transport using conditional simulation based on geostatistics (Visser et al., 2004) versus the WEPS predictions of mass transport. Fig. 1 shows the correlation between the conditional simulated maps and the WEPS-predicted maps of mass transport for the event of 9 June 2001. The correlations for the dune and the degraded site are acceptable and the correlation for the valley site is small as expected. While looking at the results (Fig. 1), the reader should keep in mind that the variogram model of the valley site was weak and that even with the stronger variogram models of the dune and the degraded sites cross correlation of several simulated mass transport maps did not result in correlation coefficients higher that 0.6. The low correlation for the valley site can be attributed to the poor quality of the variogram, the correlation of the other sites is in the line of expectations. This combined with the fact that the predicted range of mass transport intensity agrees well with the measured range (Visser et al., 2005) leads to the conclusion that WEPS in PCRaster gave good predictions in spatial variations of wind-blown mass transport, and therefore also in spatial variation of erosion and deposition.

Table 5 shows the results of the simulation of three wind erosion events using WEPS. Simulation results vary between 115 ton ha^{-1} soil loss on the degraded site and a deposition of 469 ton ha^{-1} on the valley site. For the event of 9 June deposition was predicted at all sites, whereas for the other events soil loss was predicted at the dune and the degraded site. For the valley deposition was predicted for all events. The predicted amounts of sediment transport during the event of 9 June agree well with the field measurements of mass transport and the geostatistical simulated maps of intensity of mass transport. A possible explanation for the prediction of deposition of sediment at all sites during this event is that no loose sediment on top of the soil crust was available for entrainment. On 5 June a moderate intense wind erosion event occurred, with the same average wind direction (NE) as the event of 9 June, taking along most available loose sediment. No rainfall event occurred between 5 and 9 June, so no new sediment was created. Deposition was predicted in and just before cells with a low transport capacity due to a large roughness or vegetation cover. Would the wind have come from another direction, the previously deposited sediment would have been available for re-entrainment. The cover of trees and shrubs, which are scattered over the research site combined with the geomorphic situation of the research site (downwind from a partly degraded pediplane, resulting in large amounts of incoming sediment (Visser et al., 2005)), can explain the occurrence of deposition on the valley site for all events. The dune and degraded sites lack this vegetation cover; therefore the wind can develop enough stress to entrain particles (erosion). As fewer cells with low transport capacity are present, less sediment is deposited.

Table 5 presents the simulated nutrient gains and losses related to the saltation material. When erosion occurs, considerable amounts of nutrients are lost, and when deposition occurs, large amounts of these lost nutrients can be regained. Total losses of C, N and P are

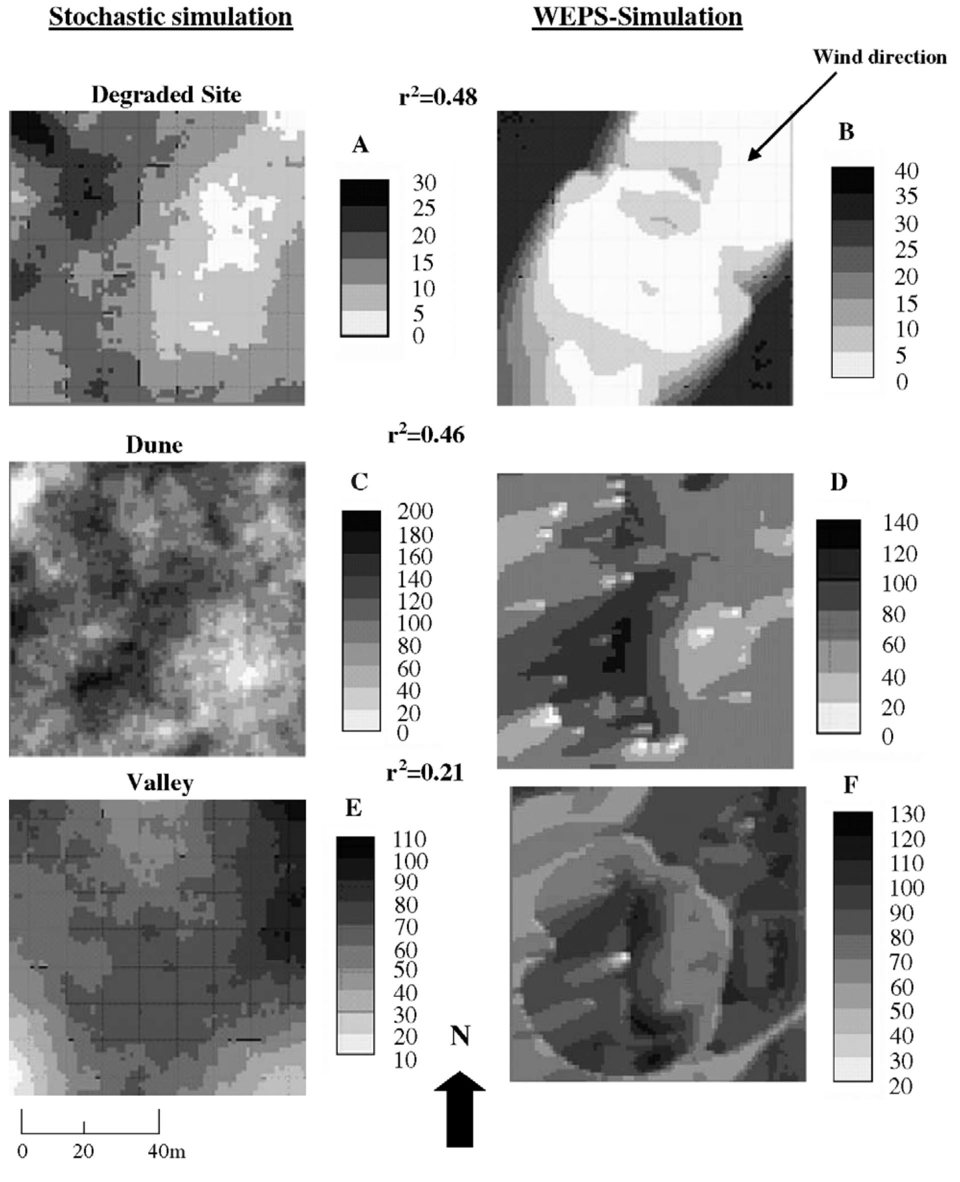

Fig. 1. Stochastic simulated (A, C and E) and WEPS-predicted (B, D and F) maps of mass transport (kg m^{-2}) for a wind erosion event on 9 June 2001 at the degraded site (A and B), the dune site (C and D) and the valley site (E and F) in the Katchari catchment in northern Burkina Faso. R^2 indicates the correlation between the two maps.

larger than those found by Bielders et al. (2002) and Sterk et al. (1996). This is related to the higher soil losses predicted by the model. According to Buerkert and Hiernaux (1998) 15 kg N and 2 kg P ha^{-1} y^{-1} are exported with crop yields from traditional cultivated fields in the Sahel. Comparing these values with the losses simulated for our research sites,

Table 5
WEPS simulated erosion and deposition (ton ha^{-1}) and total N, P and C (kg ha^{-1}) for three wind erosion events at the three sites in the Katchari catchment in northern Burkina Faso

Date		Dune	Degraded	Valley
June 9 2001	Er./Dep.	+33	+73	+469
	N-tot	+1.3	+9.9	+97.7
	P-tot	+0.4	+3.2	+2.5
	C-tot	+75.1	+9.5	+849.7
June 22 2001	Er./Dep.	–78	−77	+195.8
	N-tot	−4.6	−3.1	+19.7
	P-tot	−2.0	−3.2	+5.2
	C-tot	−74.0	−78.8	+176.8
July 3 2001	Er./Dep.	−102	−114.7	+5
	N-tot	−7.6	−6.8	+5.5
	P-tot	−4.4	−3.3	+1.7
	C-tot	−153.1	−98.4	+74.3

Positive numbers indicate deposition, negative numbers indicate erosion.

it becomes clear that with one wind erosion event 78% of the N and 100% of the P needs for crop growth may be eroded. On the other hand, these nutrients may be gained when deposition occurs.

3.3. Water erosion measurements

Table 6 shows the TE content of the sediment caught in the runoff plots. Highest TE contents were found at the valley site. Nitrate-N losses were a factor 3–10 higher at the dune site than for the valley and the degraded site. Similar results were obtained by Biaou et al. (1999). Measured nitrate-N values in runoff from aeolian deposits in a small catchment in northern Burkina Faso were up to 4 times higher than nitrate-N values in runoff from erosion crusts. In order to find out the reason for this phenomenon more research is required.

Table 6
Total runoff, total soil loss and total carbon (C), nitrogen (N), and phosphorus (P) contents of the sediment caught in the runoff plots and the total soluble N-content of the runoff water for three rainfall events at three sites in the Katchari catchment

Date	Site	Runoff (mm)	Soil Loss (kg ha^{-1})	C (mg kg^{-1})	N (mg kg^{-1})	P (mg kg^{-1})	Nitrate-N (μg l^{-1})
July 20 2001	Dune	7.5	7.0	5455	396	92	1425
	Degraded	7.2	7.5	4935	372	82	469
	Valley	5.5	6.8	7915	717	112	121
August 15 2001	Dune	10.3	3.5	4700	422	96	1316
	Degraded	18.2	9.5	6530	383	135	244
	Valley	2.9	3.0	5350	690	156	132
August 20 2001	Dune	8.3	2.0	1770	179	119	1180
	Degraded	24.2	7.5	1605	176	104	218
	Valley	24.2	9.0	5890	549	139	478

The showed values are the average of the two runoff plots.

The ER values calculated from the TE content of the trapped material are shown in Table 7. The ER for the event of 20 August 2000 are the average of all measured ER values. For each event ER values for N and P were highest at the valley site. This can be explained by the fact that the TE contents of the topsoil were measured before the onset of the rainy season and due to the continuous deposition of wind-blown sediment the new topsoil may already have been enriched in nutrients. This results in relatively higher ER values for the eroded sediment. ER values for C were not highest (Table 7) even though the absolute values of the eroded sediment were the highest. This can be explained by the fact that the topsoil already had a high C content before the onset of the rainy season due to cattle grazing (Table 1). For all sites the event of 15 August showed the largest ER values, except for the ER value for C at the dune site and for N at the valley site. For these last two ER's highest values were found at the event of 20 July. Despite the fact that most rainfall was recorded at the valley and dune sites after the event of 20 August, this event had for all sites the lowest ER values. A possible explanation is that during the event of 20 August the highest runoff and the largest amount of sediment transport were measured. More sandy material (not containing any nutrients) was transported, resulting in lower ER values. Another explanation might be that nutrients attached to the loose material on top of the crust were already removed by previous events. Furthermore, due to the high intensity rainfall, sheet flow developed during the first 5 min of the event. When the soil surface is protected by a sufficient thick layer of water, rain splash cannot exert large forces at the soil surface and the crust, in and under which fine material and nutrients are present, is not broken. So not much fine material and nutrients could be added to the material available for transport.

3.4. Water erosion modelling

Visser et al. (in press) calibrated and tested the EUROSEM in PCRaster model at the same research site as described in this research. They concluded that the model can be applied to the Sahelian situation to predict total runoff and sediment losses. Since nutrient

Table 7
Enrichment ratios (ER) For four water erosion events at three sites in the Katchari catchment

Date	Element	Dune	Degraded	Valley
July 20 2001	N	2.4	1.3	3.1
	C	3.4	2.7	1.0
	P	0.9	0.5	0.8
August 15 2001	N	2.6	3.0	3.0
	C	3.0	3.6	1.9
	P	0.9	0.8	1.5
August 20 2001	N	1.1	0.6	2.4
	C	1.1	0.9	1.3
	P	1.0	0.7	0.7
Average values used for August 20 2000	N	2.0	1.6	2.8
	C	2.5	2.4	1.4
	P	0.9	0.7	0.9

losses are closely related to the prediction of runoff (nitrate-N) and sediment (total N, P and C) and predictions for both runoff and sediment losses were acceptable, we assume that nutrient losses are also well predicted. However this assumption should be regarded with some scepticism since we used spatial average nutrient content values as input and these may not always be correct.

Table 8 shows total simulated soil and nutrient losses for the three rainfall events. For all events highest soil losses were predicted at the degraded site. These soil losses occurred due to a combination of the presence of a highly developed soil crust, which limits infiltration and increases runoff, and a lack of vegetation or mulch cover and high soil nutrient levels (Table 2).

Largest soil losses were predicted for all sites for the event of 20 August 2001, which was the largest event. The second largest event of 15 August did not result in the prediction of large amounts of soil losses at the dune and valley sites. This is related to the cultivation history of the fields. Since neither the dune nor the valley site was cultivated before 20 July, and a well developed crust limited infiltration. The valley and dune sites were hoed at 24 July and 3 August, respectively, increasing infiltration. After the event of 15 August, two large rainfall events occurred, during which the newly developed soil crust could further developed. At the onset of the rainfall event of 20 August, both the dune and valley sites were covered again with a well developed crust.

Nutrient losses were highest at the degraded site, as was expected in relation to the large sediment losses. N losses due to dissolved transport of nitrate are negligible compared with the N losses in the sediment. This conclusion corresponds with the results found by Biaou et al. (1999) in northern Burkina Faso. They found that N losses in dissolved form only represented 0.3% of the total N losses.

Table 8
Simulated erosion (ton ha^{-1}) and nutrient losses (kg ha^{-1}) for three rainfall events at three sites in the Katchari catchment in northern Burkina Faso

Date		Dune	Degraded	Valley
July 20 2001	Erosion	−0.04	−0.21	−0.01
	N-tot	−0.02	−0.08	−0.01
	P-tot	−0.00	−0.02	−0.00
	C-tot	−0.24	−1.05	−0.01
	Nitrate-N	$-\ll 10^{-3}$	$-\ll 10^{-3}$	$-\ll 10^{-3}$
August 15 2001	Erosion	−0.02	−0.32	−0.01
	N-tot	−0.01	−0.95	−0.00
	P-tot	−0.00	−0.04	−0.00
	C-tot	−0.07	−2.07	−0.03
	Nitrate-N	$-\ll 10^{-3}$	$-\ll 10^{-3}$	$-\ll 10^{-3}$
August 20 2001	Erosion	−0.05	−0.87	−0.05
	N-tot	−0.01	−0.14	−0.03
	P-tot	−0.01	−0.13	−0.00
	C-tot	−0.08	−1.09	−0.15
	Nitrate-N	$-\ll 10^{-3}$	$-\ll 10^{-3}$	$-\ll 10^{-3}$

Compared with the nutrient exports due to crop yields in the Sahel, nutrient losses by the three simulated rainfall events are small.

3.5. Combination of wind and water erosion

For the simulation of the combined wind/water erosion event on 20 August 2000 (Table 9), first the wind erosion event is simulated. As soon as rainfall started, the wind erosion model is interrupted and all sediments in motion are deposed. Input maps of the spatial distribution of loose sediment and nutrients were prepared and the water erosion model is run. Net deposition of sediment and nutrients under influence of the wind occurred at the dune site, whereas water erosion resulted in a net soil loss which is negligible compared with the deposition of wind-blown sediment. Fig. 2 shows the spatial distribution of erosion and deposition by wind and water at the dune for the event of 20 August 2000. From this figure it becomes clear that despite a net deposition under influence of the wind at the dune site, large areas with net erosion can be identified. Deposition generally occurs in concentrated areas. For water erosion the same pattern is found. Small amounts of soil are eroded from the slopes and deposed in the down slope area or in the pool areas. Especially in the pool in the south-eastern part of the field much sediment is deposed. At the wind erosion/deposition map a net erosion for this area is shown, and net effect of wind and water erosion is approximately zero in this area. Here it is shown that despite the fact that soil losses by water erosion can be negligible at the field scale, its role can be significant when spatial variation within that field is considered.

At the degraded site, wind erosion caused 99% of the total soil loss, whereas at the valley site soil loss by water contributed 25% of total soil loss (Table 9). At the valley site wind-blown sediment transport occurred only at a small part of the research site, the crop cover hindered wind-blown sediment transport at the rest of the site. Therefore, sediment

Table 9
Simulated erosion and deposition and nutrient gains and losses by wind and water during the event of 20 August 2000 at three sites in the Katchari catchment, northern Burkina Faso

	Dune	Degraded	Valley
Soil (ton ha^{-1})			
Wind	+29.85	−23.65	−0.03
Water	−0.01	−0.28	−0.01
Total	+29.84	−23.93	−0.04
N (kg ha^{-1})			
Wind	+6.27	−8.69	−0.01
Water	−0.01	−0.21	−0.01
Total	+6.26	−8.90	−0.02
P (kg ha^{-1})			
Wind	+2.24	−3.80	−0.00
Water	−0.01	−0.05	−0.00
Total	+2.23	−3.85	−0.00
C (kg ha^{-1})			
Wind	+171.90	−119.00	−0.11
Water	−0.10	−1.90	−0.06
Total	+171.80	−120.90	−0.17

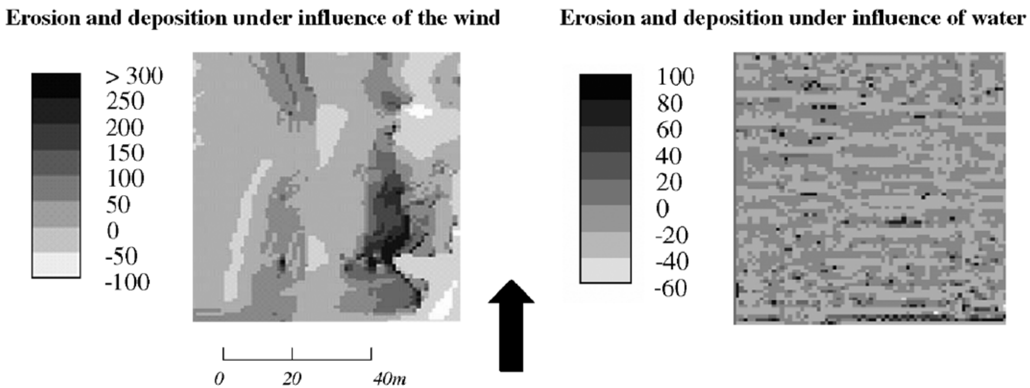

Fig. 2. Spatial distribution of erosion (negative) and deposition (positive) (kg m^{-2}) by wind and water in the dune site in the Katchari catchment, northern Burkina Faso for the combined wind and water erosion event of 20 August 2000.

and nutrient losses at the valley site due to the wind were very low, increasing the relative importance of water erosion at this site. Comparing nutrient losses by wind and water at the degraded and dune sites it becomes clear that wind erosion caused largest nutrient losses and in comparison the losses of water erosion were negligible. Also in the case that deposition of wind-blown sediment occurs nutrient losses by water erosion are negligible in comparison with the deposited amounts. However one should keep in mind that soil and nutrient losses due to water erosion occur no matter whether the field is cultivated or abandoned and that soil and nutrients are transported with the runoff to the nearest stream and leave the area. So nutrients lost by water erosion are forever lost for the catchment.

The average travelling distance of saltating particles ranges from 10 to several hundred meters (Bagnold, 1941). Once picked up by the wind saltating particles are moved in the downwind direction until they reach an obstacle like trees or bushes and are deposited. It can be that the saltating particles leave the field and are deposited in an adjacent field or fallow, or the process results in a redistribution of sediment within the farmers' field (Visser et al., in press). In northern Burkina Faso the landscape can best be described as parkland with trees and bushes scattered over the area, even on cultivated fields. However, generally cultivated fields have a less dense coverage of trees and shrubs, so those fields serve as a source of sediment and nutrients for wind-blown transport. This sediment is generally deposited in adjacent fallow areas, which have a denser shrub coverage and serve as a sink. When farmers abandon their exhausted fields and start cultivating a fallow area the source/sink relation is reversed. Therefore, saltation transport can only result in a local redistribution of soil particles and nutrients. On a larger time scale the net erosion/deposition of nutrients under influence of saltation transport may be close to zero. However, this crop/fallow system only functions when a sufficient large area of fallow land is present, otherwise the regional budget of nutrient related to saltating particles becomes negative (Sterk et al., 1996).

Even with a correct balance between fallow and cultivated land, wind erosion can be responsible for large losses of nutrients and fine particles over a larger time scale. Although suspension transport by wind was not discussed in this article, its impact should not be overlooked. With each event suspended dust, rich in nutrients, is lifted up until a height of several hundred meters and may be carried over long distances. Several authors reported observation of dust clouds from West-Africa to cross the Atlantic Ocean (Carlson and Prospero, 1972; Westphal et al., 1988). These nutrients are lost from the area. However, also input of dust occurs during the Harmattan (Herrmann et al., 1994; Rajot, 2001). These dust deposits origin from the Sahara desert and are rich in K but poor in P. Rajot (2001) argued that for western Niger the net balance for nutrients from suspension is positive under current land use conditions. But Sterk et al. (1996) argued that it remains still unclear whether there is a net loss or gain of dust and nutrients due to suspension transport in the Sahel.

4. Conclusion

The physically based model of WEPS in PCRaster can predict patterns of erosion and deposition due to wind-blown sediment transport. Depending on wind direction, crusting pattern and vegetation cover net erosion or deposition can occur. When erosion occurs, considerable amounts of nutrients are lost (with one wind erosion event 77.5% of the N and 100% of the P needs for crop growth may be eroded).

ER values of sediment transported by water are generally higher when more runoff occurs, but further depend on the availability of fine particles and the moment of overland flow development. Deposition of wind-blown sediment may result in a topsoil which is enriched in nutrients. When ER's for water eroded sediment are calculated based on nutrient contents of soil samples taken before the onset of the rainy season, ER values will be relatively high, which may lead to an overestimation of the soil degradation. Of course this is also true for wind erosion.

Soil loss by water erosion is closely related to the crust type present, which regulates infiltration and thus runoff. N losses due to dissolved transport of nitrate are negligible compared with the N loss due to sediment transport. With three rainfall events only 0.7% of N and 0.006% of P needs for crop growth are eroded.

Despite a net erosion or deposition by both wind and water erosion at the scale of a field, within the field areas with erosion and deposition can be identified. At field scale soil and nutrient losses by water erosion are negligible in comparison with wind erosion. However, the role of water erosion can be significant when spatial variation within a field is considered. Furthermore soil and nutrient losses by water are directed to the nearest stream and leave the catchment. These nutrients are forever lost for the area. Sediment transport by wind in saltation mode results in the largest soil and nutrient loss at the time scale of an event.

References

Bagnold, R.A., 1941. The Physics of Blown Sand and Desert Dunes. Methuen, London.

Biaou, A.C., et al., 1999. Érosion hydrique et transfert de solutés en milieu Sahélien. Sud-Sciences & Technologies 4, 18–28.

Bielders, C.L., Rajot, J.L., Amadou, M., 2002. Transport of soil and nutrients by wind in bush fallow land and traditionally managed cultivated fields in the Sahel. Geoderma 109, 19–39.

Buerkert, A., 1995. Effects of crop residues, phosphorus and spatial variability on yield and nutrient uptake of pearl millet in southwest Niger. PhD dissertation Thesis. University of Hohemheim, Germany, STUTTGART, 272 pp.

Buerkert, A., Hiernaux, P., 1998. Nutrients in west African Sudano–Sahelian zone: losses transfers and role of external inputs. Zeitschrift für Planzenernahrung und Bodenkunde 161 (4), 365–383.

Carlson, T.N., Prospero, J.M., 1972. The large-scale movement of Saharan air outbreaks over the northern equatorial Atlantic. Journal of Applied Meteorology 11, 283–297.

Cogle, A.L., et al., 2002. Soil management for alfisols in the semi-arid tropics: erosion, enrichment ratios and runoff. Soil Use and Management 18, 10–17.

Courel, M.F., 1977. Étude géomorphique des dunes du Sahel; Niger Nord occidental et Haut-Volta Septentrional. Thèse de troisième cycle. Université de Paris, Paris, France.

De Jager, A., Nandwa, S.M., Okoth, P.F., 1998. Monitoring nutrient flows and economic performance in African farming systems (NUTMON): I. Concepts and methodologies. Agriculture Ecosystems & Development, vol. 71, pp. 37–48 (Nutrient balances as indicators of productivity and sustainability in sub-Saharan African agriculture).

De Jong, K., 1997. PCRaster homepage; info, software and manuals, http://www.modelkinetix.com/modelmaker/.

Dregne, H.E., Kassas, M., Rozanov, B., 1991. A new assessment of the world status of desertification. Désertification Control Bulletin 20, 6–18.

Geelhoed, R., 1995. Les pertes de nutriments dans le ruissellement et le sédiment et l'importance relative d'entraînement; une étude de champ près de Kaibo Sud, Burkina Faso. MSc-Thesis Thesis, Wageningen University, Wageningen, 25 pp.

Hagen, L.J., 1991. A wind erosion prediction system to meet user needs. Journal of Soil and Water Conservation 46, 106–111.

Hagen, L.J., 1996. WEPS, USDA Wind Erosion Prediction System. Technical Documentation. USDA-ARS Wind erosion research unit, Kansas, USA.

Hashim, G.M., Coughlan, K.J., Syers, J.K., 1998. On site nutrient depletion: an effect and a cause of soil erosion. In: Kerr, J. (Ed.), Soil Erosion at Multiple Scales: Principles and Methods for Assessing Causes and Impacts. CAB International, pp. 207–221.

Herrmann, L., stahr, K., Sivakumar, M.K.V., 1994. Dust deposition on soils of southwest Niger. In: von Oppen, M. (Ed.), Wind Erosion in West Africa: the Problem and its Control. Margraf Verlag, Weikersheim, Germany, pp. 35–47.

Karambiri, H., Ribolzi, O., DelHoume, J.P., Ducloux, J., Coudrain-Ribstein, A., 2003. Importance of soil surface characteristics on water erosion in a small grazed Sahelian catchment. Hydrological Processes 17, 1495–1507.

Lal, R., 1998. Soil erosion impact on agricultural productivity and environmental quality. Critical Reviews in Plant Sciences 17, 319–464.

Leys, J.F., McTainsh, G., 1994. Soil loss and nutrient decline by wind erosion — cause for concern. Australian journal for Soil and Water Conservation 7, 30–35.

Morgan, R.P.C., Quinton, J.N., Rickson, R.J., 1992. EUROSEM Documentation Manual. Version 1. Silsoe College, Silsoe.

Morgan, R.P.C., Quinton, J.N., Smith, R.E., Govers, G., Poesen, J.W.A., Auerswald, K., Chisci, G., Torri, D., Styczen, M.E., 1998. The European Soil Erosion Model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments. Earth Surface Processes and Landforms 23, 527–544.

Nandwa, S.M., Bekunda, M.A., 1998. Research on nutrient flows and balances in west Africa: state-of-the-art. Agriculture, Ecosystems & Environment, vol. 71, pp. 5–19 (Nutrient balances as indicators of productivity and sustainability in sub-Saharan African agriculture).

Nicoleson, S.E., 2001. Climatic and environmental change in Africa during the last two centuries. Climate Research 17, 123–144.

Rajot, J.L., 2001. Wind blown sediment mass transport of Sahelian village land units in Niger. Bulletin de la Societé Géologique de France 172, 523–531.

Ribolzi, O., et al., 2003. Hydrochemistry of runoff and subsurface flow within Sahelian microdunes. European Journal of Soil Science 54, 1–12.

Sterk, G., Haigis, J., 1998. Farmers' knowledge of wind erosion processes and control methods in Niger. Land Degradation and Development 9, 107–114.

Sterk, G., Raats, P.C., 1996. Comparison of models describing the vertical distribution of wind-eroded sediment. Soil Science Society of America Journal 60, 1914–1919.

Sterk, G., Stein, A., 1997. Mapping wind-blown mass transport by modelling variability in space and time. Soil Science Society of America Journal 61 (1), 232–239.

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

Stroosnijder, L., 1995. Quantification of nutrient erosion. In: ?? (Editor), Conference on Erosion and Land Degradation in the Mediterranean, Aveiro, Portugal.

Thiombiano, L., 2000. Etude de l'importance des facteurs édaphiques et pédopaysagiques dans le développement de la désertification en zone Sahélienne du Burkina Faso. Thèse de docteur d'état ès sciences naturelles Thesis. L'Université de Cocody, Abidjan.

Valentin, C., Bresson, L.M., 1992. Morphology, genesis and classification of surface crusts in loamy and sandy soils. Geoderma 55, 225–245.

Van Dijck, S., Karssenberg, D., 2000. EUROSEM in PCRaster. http://www.geog.uu.nl/pcraster/runoff/eurosem/.

Visser, S.M., Leenders, J.K., Leeuwis, M., 2003. Farmers' perceptions of erosion by wind and water in northern Burkina Faso. Land Degradation and Development 14, 123–132.

Visser, S.M., Sterk, G., Snepvangers, J.J.J.C., 2004. Spatial variation in wind-blown sediment transport in geomorphic units in northern Burkina Faso using geostatistical mapping. Geoderma 120, 95–107.
Visser, S.M., Sterk, G., Karssenberg, D., 2005. Wind erosion modelling in a Sahelian environment. Journal of Environmental Modelling and Software 20, 69–84.
Visser, S.M., Sterk, G., Karssenberg, D., in press. Modelling water erosion in the Sahel; application of a physical model on a gentle sloping area. Earth Surface Processes and Landforms (Published online 26 Aug. 2005).
Westphal, D.L., Toon, O.B., Carlson, T.N., 1988. A case study of mobilisation and transport of Saharan dust. Journal of Atmosphere Sciences 45, 2145–2175.
Williams, M.A.J., Balling, R.C., 1994. Interactions of Desertification and Climate. Geneva, Switzerland. 230 pp.
Wortmann, C.S., Kaizzi, C.K., 1998. Nutrient balances and expected effects of alternative practices in farming systems of Uganda. Agriculture, Ecosystems & Environment, vol. 71, pp. 115–129 (Nutrient balances as indicators of productivity and sustainability in sub-Saharan African agriculture).
Zobeck, T.M., Fryrear, D.W., 1986. Chemical and physical characteristics of wind-blown sediment. II Chemical characteristics and total soil nutrient discharge. Transactions of ASAE 29, 1037–1041.