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WIND EROSION REDUCTION BY SCATTERED WOODY VEGETATION IN FARMERS' FIELDS IN NORTHERN BURKINA FASO

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ABSTRACT

Wind erosion is an important soil degradation process on agricultural fields in the Sahel and is strongly affected by scattered woody vegetation. This paper analyses the effect of scattered vegetation on sediment transport in agricultural fields in northern Burkina Faso. A model was developed to simulate the changes in wind speed and sediment transport around shrubs and trees. The model was applied by using field measurements on wind speed, wind direction, and sediment transport, obtained from two farmers' fields during the rainy season of 2003. Vegetation characteristics and the density of vegetation elements differed per field. The model was used for scenario studies to test the effect of height, number, element type and spatial arrangement of vegetation elements on aeolian sediment transport. The local effects of vegetation elements on wind speed and sediment transport are small compared with the effects caused by the changes in the aerodynamic roughness length and changing wind speed at a larger scale. With relatively small changes in the characteristics of scattered woody vegetation, sediment transport can change considerably. An optimal arrangement of vegetation elements in an area in itself does not exist; it is an interrelation between the number of vegetation elements, the silhouette area and the type of vegetation elements present. This interrelation makes the use of scattered vegetation as a wind erosion control strategy attractive, as it fits in a variety of farming systems and can easily be adapted to specific needs of farmers. Therefore, scattered woody vegetation can be used to reduce sediment transport. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: Sahel; wind erosion control; aeolian sediment transport; scattered vegetation; parkland system

INTRODUCTION

The Sahelian zone of Africa is the region that is globally most subjected to land degradation (Darkoh, 1998), with wind erosion being the most important soil degradation process (Visser & Sterk, 2007). In the Sahel, wind erosion occurs mainly during two periods of the year: in the dry season (October–April) and in the early rainy season (May–July). During the dry season, the Sahel is invaded by the so-called Harmattan, dry and rather strong trade winds, that blow in the south-westerly direction off the Sahara desert. These winds mostly carry much dust from the Sahara and cause only moderate wind erosion in the Sahel (Michels *et al*., 1995). The wind erosion that occurs at the start of the rainy season is caused by strong and generally short duration (10–30 min) storms that precede convective rainstorms. The soil movement that occurs during these events is much more intense than the soil movement during the 'Harmattan' (Michels *et al*., 1995).

By using control measures, wind erosion can be reduced. Wind erosion control measures either decrease the strength of the wind at the soil surface or increase the resistance of the soil surface, or both. However, at present, adoption of wind erosion control measures by Sahelian farmers is low (Sterk & Haigis, 1998; Bielders *et al*., 2001), as most recommended measures do not fit into the local farming systems (Baidu-Forson & Napier, 1998). Thus, there is a need for wind erosion control measures that actually fit into the local farming systems and do not require much additional input of labour and resources (Rinaudo, 1996).

Studies carried out in Niger (Taylor-Powell, 1991; Sterk & Haigis, 1998; Bielders *et al*., 2001) and in Burkina Faso (Leenders *et al*., 2005a) reported the farmers' interest in reducing wind erosion through regeneration of the natural woody vegetation in cropland. Landscapes in which scattered vegetation of trees and shrubs occurs in cultivated or recently fallowed fields are called a 'parkland system'. Unfortunately, much of the natural woody vegetation in the Sahel disappeared because of drought and deforestation (Tougiani *et al*., 2009). Development projects started to encourage farmers to regenerate the natural vegetation (Rinaudo, 2007). In the south of Niger, natural regeneration of woody vegetation through farmer-managed natural regeneration (FMNR) was actually used as a wind erosion control strategy (Rinaudo, 1996). The FMNR strategy was successful in reducing wind erosion and improving crop yields (Rinaudo, 2007; Tougiani *et al*., 2009) but was developed from trial and error testing. Given the site-specific conditions during its development, it is uncertain whether this strategy can be transferred to other places, where environmental conditions may be different. Moreover, an important

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question related to FMNR concerns the density of trees required in a field for sufficient protection (Rinaudo, 2007; Tougiani *et al*., 2009). Initially, a density of 40 trees per ha was recommended, but Tougiani *et al*. (2009) reported that tree densities on some farms exceed even 150 trees per ha.

Before promoting the parkland system as a wind erosion control strategy, the effect of scattered woody vegetation on wind erosion should be understood and quantified. Data of measurements on wind speed and sediment transport around isolated vegetation elements showed that the morphology of elements determines the effects of these elements on wind speed and sediment transport (Leenders *et al*., 2007). Two types of elements can be distinguished: elements with a canopy starting at the soil surface (‘shrubs’) and elements that have a distinctive trunk with a canopy above it (‘trees’). Shrubs were found to reduce wind speed and sediment transport up to 7·5 times the height of the element (Leenders *et al*., 2007; Leenders *et al*., 2011). In addition, material already in transport was trapped effectively by shrubs (Leenders *et al*., 2007). Trees showed a different effect on wind speed and sediment transport. Below the canopy and around the trunk, streamlines are contracted resulting in an increased wind speed and sediment transport. In addition to these local effects, the presence of trees and shrubs has also an effect at the larger scale (Kainkwa & Stigter, 1994). Both trees and shrubs extract momentum from the wind, which diminishes the wind speed in an area (Dupont *et al*., 2014). As trees are generally larger in height and width than shrubs, it is expected that trees are more effective in reducing the wind speed in an area than shrubs (Leenders *et al*., 2007).

The degree of erosion protection by different vegetation elements and the optimal vegetation arrangement to protect Sahelian cropland from wind erosion are currently unknown. The aim of this study was to model wind speed and sediment transport reductions by different patterns and densities of scattered woody vegetation in farmers’ fields in the north of Burkina Faso.

MATERIALS AND METHODS

Study Area

During the rainy season of 2003, experimental work was carried out in two agricultural fields, located at approximately 12 km (field A) and 7 km (field B) east of Dori in north Burkina Faso. The area is part of the southern Sahelian zone, which is characterized by high temperatures all year round and a short rainy season, from June to September. The average annual rainfall is 420 mm, but variability in annual rainfall is high.

The soil texture in the experimental fields is loamy sand. Field A has 82·1% sand, 13·6% silt and 4·3% clay in the topsoil (0–5 cm), and field B has 85·7% sand, 11·8% silt and 2·5% clay in the topsoil. The main crop in both experimental fields was pearl millet (*Pennisetum glaucum* (L.) R. Br.), which is normally sown after the first major rain event in the early rainy season. Within both fields, natural vegetation was present. The most common vegetation species were *Acacia tortilis* ssp. *raddiana* (Savi), *Maerua crassifolia* Forssk. and *Balanites aegyptiaca* (L.) Delile in field A and *Piliostigma reticulatum* (DC.) Hochst., *Faidherbia albida* (Delile) A. Chev., *B. aegyptiaca* (L.) Delile and *Ziziphus mauritiana* Lam. in field B.

Field Measurements

In both fields, a detailed vegetation survey was carried out in a plot of 100 × 100 m. The vegetation species were determined, and the following characteristics that influence wind speed and sediment transport were measured: trunk height and trunk width (for trees only), total height, canopy width (both in NS and EW directions), the location in the plot, and optical porosity of the canopy. The latter was estimated using digital pictures and image software, similar to the method of Kenney (1987) The species, height and width of the vegetation in the rest of the experimental fields were also determined.

Wind speed on both fields was measured with a cup anemometer that was mounted on a mast at 3·25 m. Every 5 s, wind speed was sampled, and the average value was registered every minute. Wind direction was measured at the same height and time intervals with a wind vane. A tipping bucket rain gauge was used to measure rainfall every minute. The rainfall data were used to determine the duration of a windstorm prior to rainfall.

Sediment transport was measured with two saltiphones (Spaan & Van den Abeele, 1991), which is a robust sensor that counts impacts of saltating particles onto a microphone. It can be used for detecting periods and intensities of saltation transport. The two saltiphones were placed 3 m in NE and SW directions of the meteorology mast, and the centre of the microphones was positioned at 0.10 m above the surface. The total mass of particle flux was measured with 17 Modified Wilson and Cooke (MWAC) catchers (Sterk & Raats, 1996). Sediment transport was measured with separate traps at five heights, at 0·05, 0·12, 0·19, 0·26 and 0·75 m above the soil surface. For more details on the MWAC catcher, refer to Sterk & Raats (1996).

For every storm and catcher, mass flux densities ($kg\,m^{-2}\,s^{-1}$) were calculated for each height from the weights of the trapped materials, the area of the opening of the inlet tube of the catcher and the event duration. Vertically integrated mass flux at the sampling location ($kg\,m^{-1}\,s^{-1}$) was determined by fitting a curve through the mass flux densities and integrating this curve over height (Sterk & Raats, 1996; Leenders *et al*., 2007).

The 17 MWAC catchers were regularly distributed in the $100 \times 100\text{-}m^2$ plots within both experimental fields (Figure 1). In field A, the mast with the cup anemometers, a wind vane, a tipping bucket and saltiphones was placed at the western side of the plot. This guaranteed that the measured wind profile was adjusted to the field roughness conditions because normally, the main wind direction during a storm event is east. For the same reason, the meteorology

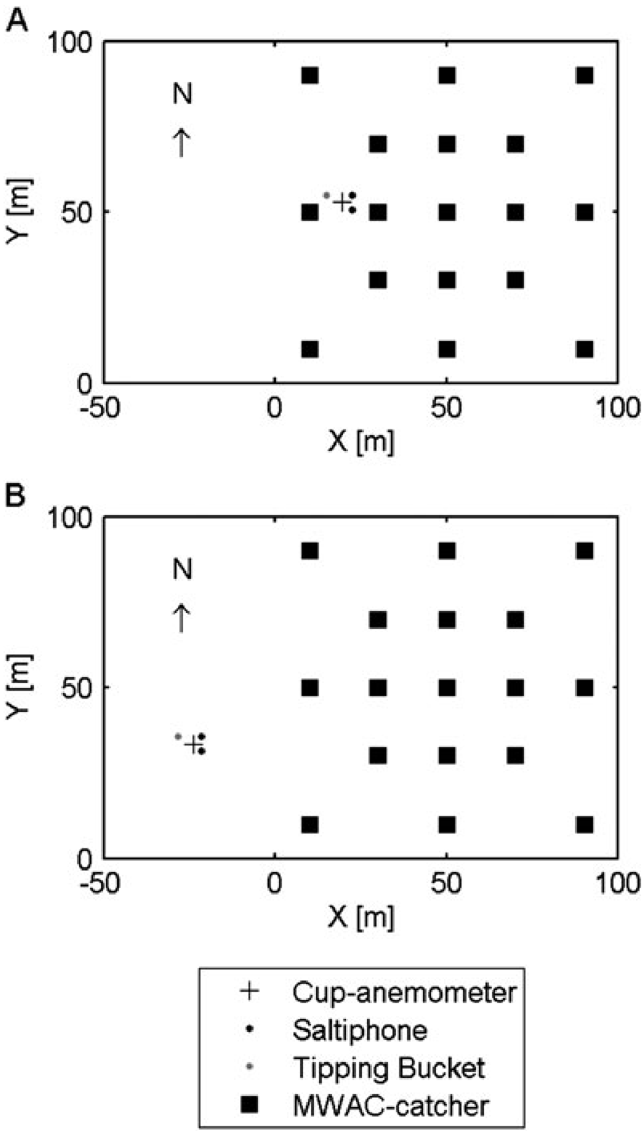

Figure 1. Location of equipment in experimental site (A) field A and (B) field B.

mast was placed just outside the plot, in the western part of the experimental field B.

Model Description

The model of Leenders *et al.* (2011) was used to simulate sediment transport in the two 100×100-m^2 plots. This model was developed to simulate sediment transport around a single, shrub-type, vegetation element during storm events. The model calculates the effect of the vegetation element on wind speed and sediment transport for each minute during a storm event. It is spatially explicit and uses a grid size of 0·1 m. The model did not yet include the effects of trees.

The model uses the sediment transport formula of Radok (1977) to relate sediment transport to wind velocity:

$$Q = A{\cdot}e^{t \cdot u} \tag{1}$$

where Q is the mass flux (kg m^{-1} s^{-1}), u is the wind speed (m s^{-1}), and A (kg m^{-1} s^{-1}) and t (s m^{-1}) are empirical constants. The driving variable for sediment transport in the model is wind speed, and not friction velocity, because the measured sediment transport was well related to wind speed at short timescales (Leenders *et al.*, 2005b). In addition, wind speed is measured easily at short time intervals and in the areas obstructed by roughness elements. Therefore, when modelling temporal variability and spatial patterns in sediment transport during storm events, using wind speed as a driving variable is easier than using friction velocity. Moreover, when the shear stress partitioning theory (Marshall, 1971) is applied, the average reduction in shear stress caused by the vegetation obstacles is calculated, which is a good approach when there is a homogeneous distribution of obstacles and when the average sediment transport for such a field is quantified. However, when the actual patterns of sediment transport are quantified in fields with heterogeneous vegetation distributions, the zones of reduced wind speed in the lee of obstacles need to be quantified, which cannot be performed with the shear stress partitioning theory.

In the Leenders *et al.* (2011) model, the areas around a shrub in which wind speed and sediment transport are affected are represented by ellipses (Figure 2). In the lee of the shrub, the wind speed reduction zone is modelled with a semi-ellipse. The origin of the entire ellipse is positioned at the centre of the shrub. Leeward of the shrub, the reduction zone extends up to 7·5 times the height (H) of the shrub. At the sides of the shrub, lateral to the mean wind direction, zones of increase in wind speed and sediment transport are also modelled by ellipses. The major axis of these ellipses is set equal to the width of the vegetation element parallel to the wind direction (W_x), and the minor axis is equal to the half width of the vegetation element lateral to the wind direction (W_y). The dimensions of these zones of change in wind speed and sediment transport were based on field measurements around vegetation elements (Leenders *et al.*, 2007).

The model calculates factors of change in wind speed (φ) in each zone that is influenced by the vegetation element. The value of this reduction factor depends on the position within the (semi) ellipse (Leenders *et al.*, 2011). The φ factor is subsequently used to calculate an adapted wind speed around the shrub. With Radok's transport equation (Equation 1), the adapted wind speed is converted into the sediment transport around the vegetation element. This sediment transport is normalized with the sediment transport of unobstructed flow to calculate a sediment transport change factor (Ψ). For the details of this modelling around isolated shrubs, refer to Leenders *et al.* (2011).

For modelling the effects of several vegetation elements in a real agricultural field, the model needed to be adapted to include the following three aspects: (i) the local effects of tree-type vegetation elements (elements with a canopy above a trunk); (ii) a parameterization to enable overlapping wake zones of vegetation elements; and (iii) the effects of vegetation elements on the average wind speed in an area.

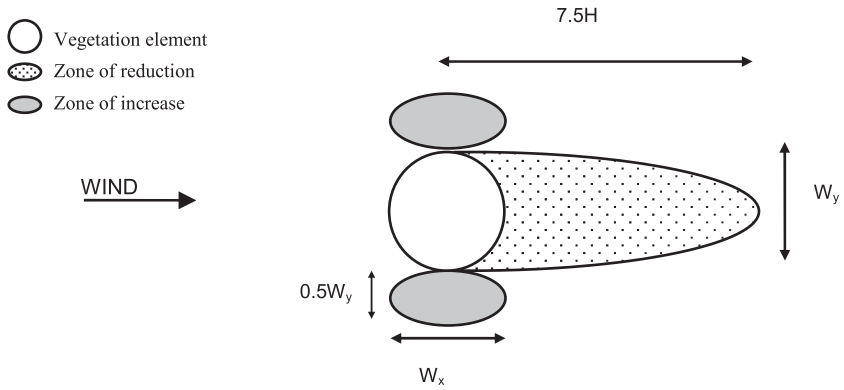

Figure 2. Spatial representation of zones of increase and reduction in sediment transport in the vicinity of a shrub. The dimensions of the zones are a function of the height of vegetation element (H), the width of the vegetation element in the direction of the wind (W_x) and the width of the vegetation element orthogonal to the direction of the wind (W_y).

First, the local effects of trees on wind speed and sediment transport were included in the model. This parameterization was based on field measurements of wind speed around the trunk of a tree (Leenders *et al.*, 2007). Because of the contraction of the flow below the canopy, around the trunk, the wind speed is accelerated and results in a zone of increasing wind speed, which was modelled by an ellipse (Figure 3). Windward, the wind speed was affected up to 0·5 times the trunk height. Leeward, this was set up to five times the trunk height. Sideward, the influence was modelled to affect up to two times the diameter of the trunk (Figure 3). In this zone, wind speed change (φ) was modelled with a quadratic curve:

$$\varphi = -0{\cdot}30\left(\left(\frac{x}{\alpha h_T}\right)^2 + \left(\frac{y}{2 d_T}\right)^2\right)^2 + 1{\cdot}30 \qquad (2)$$

where x is the coordinate of the increase zone along the wind direction, y the coordinate of the increase zone lateral to the wind direction, h_T the height of the trunk, and d_T the diameter of the trunk. The coefficient α was 0·5 windward and 5·0 leeward, indicating the boundaries of the zone of increase in wind speed in front of and behind the trunk. The coefficients −0·30 and 1·30 in Equation 2 result in an average φ of 1·2, which is in agreement with experimentally derived values (Leenders *et al.*, 2007).

Second, the overlapping of zones of influence of several vegetation elements was included in the model. It is not known how this exactly should be quantified, but it was assumed that when two vegetation elements influence wind speed in the same area, there is a stronger effect than that created by one element. Hence, this effect was simply incorporated by multiplying the wind speed factors (φ) of the different influence zones.

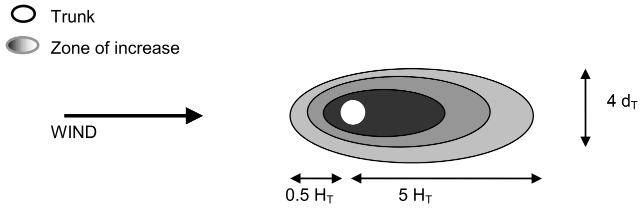

Figure 3. Spatial representation of zone of increase in sediment transport in the vicinity of a tree. The dimensions of the zone are a function of the height (H_T) and diameter of the trunk (d_T).

Finally, the effects of scattered vegetation elements in an area on the average wind speed were modelled by combining the exposure correction method of Wieringa (1976) with the aerodynamic roughness model of Lettau (1969). The method of Wieringa (1976) is based on the validity of the logarithmic wind profile in an area (area 1) with certain aerodynamic roughness, expressed by the roughness length $z_{0(1)}$ (m). The method extrapolates the known average wind speed in area 1 (U_1), to an area where the aerodynamic roughness is different because of different arrangements and characteristics of the roughness elements (area 2). From the measured wind profile in area 1, the wind speed is calculated at a height where wind speed is considered uniform, and local perturbations related to roughness elements are negligible (e.g. 100 m). The wind velocity near the ground surface at area 2 is calculated with Equation 3:

$$U_2 = U_1 \cdot \frac{\ln\left(100/z_{0(1)}\right)}{\ln\left(z/z_{0(1)}\right)} \cdot \frac{\ln\left(z/z_{0(2)}\right)}{\ln\left(100/z_{0(2)}\right)} \qquad (3)$$

where U_2 is the average wind speed in area 2 at station height z, and $z_{0(2)}$ is the aerodynamic roughness length at area 2.

The change in aerodynamic roughness length (z_0) was estimated with the model of Lettau (1969)

$$z_0 = \frac{0.5 \cdot \overline{h} \cdot s}{S} \qquad (4)$$

where $\overline{h}$ is the average height of the vegetation elements (m), s the silhouette area of the average obstacle (m^2), and S is the specific area, or lot area (m^2) measured in the horizontal plane, corrected for the number of vegetation elements (n). If n is the total number of roughness elements on a site of total area B, then $S = B/n$. The silhouette area of the average obstacle (s) is calculated by multiplying the average height of the obstacle ($\overline{h}$) with the average width, lateral to the wind direction ($\overline{w}$), corrected for the porosity of the element ($\overline{\theta}$). The numerical factor of 0·5 in Equation 4 corresponds to the average drag coefficient of the characteristic individual obstacle.

To save computation time for the model at field scale, the model grid size used in this study was set to 0·2 m instead of 0·1 m. Because of this grid size, the elements smaller than 0·5 m in height were not taken into account within the analysis of this study. Such small elements were assumed to have a minimal effect on wind speed and sediment transport but would increase the computation time.

It should be mentioned that the model, as such, simulates the variability in sediment transport because of the presence of vegetation elements only. Topography, an important factor for sediment transport variability (Sterk *et al.*, 2004), is not included in the model yet. At present, the simulated field is entirely flat, and this does not change during a wind erosion event. Moreover, the model assumes an omnipresent availability of sediment material, which is not necessarily true in the area (Visser *et al.*, 2004).

Model Performance and Scenario Testing

First, the developed model was tested for experimental plots for storm events that were measured in the rainy season of 2003. One storm event was selected and used to run scenarios to determine the effects of scattered vegetation on sediment transport. First, a hypothetical scenario of a bare field without any scattered vegetation was run to test the influence of vegetation removal on wind speed and sediment transport. Next, four types of vegetation cover scenarios were run. Type I scenarios tested the effect of the silhouette area of vegetation elements on sediment transport. Type II scenarios tested the effect of the number of vegetation elements. Scenarios of type III tested the effect of different percentages of tree and shrub-type vegetation elements, ranging from a scenario where all vegetation elements are shrubs to a scenario where there are only trees. Finally, with type IV scenarios, the spatial arrangement of vegetation elements was tested.

RESULTS

During the rainy season of 2003, a total of ten storms were recorded. Three storms were selected for modelling (27 May, 26 June and 1 July). Duration and intensity of the storms differed between the two experimental plots (Table I), indicating the spatial variability of storm characteristics in the area. This spatial variability was also reflected in the measured sediment transport both within and between the plots. For example, the event of 26 June showed an almost equal average wind speed at both plots, but the average sediment transport at plot A was nearly twice as much as that at plot B. This difference can be partly explained by the difference in turbulence intensity (wind speed standard deviation divided by the average wind speed), which was 0·160 in plot A and 0·126 in plot B. A higher turbulence intensity means more strong gusts that cause intense sediment transport, resulting in a higher sediment transport for the plot.

The pattern of natural woody vegetation present in both experimental plots was scattered (Figure 4). Most of the vegetation elements comprised shrubs (78% in plot A and 87% in plot B). The density of vegetation elements larger than 0·5-m height was 129 (101 shrubs and 28 trees) elements per ha in plot A and 70 (62 shrubs and 8 trees) elements per ha in plot B. The characteristics of the vegetation element are given in Table II. The optical porosity changed during the rainy season, as the canopy became denser because of the growing of leaves. At the start of the rainy season, the optical porosity was about 25% less compared with the end of the rainy season. The surface cover in the open space between the trees and shrubs was bare by the end of May but increased to low crop canopy cover (<10%) by early July, after the pearl millet crop had emerged. However, it was assumed that surface roughness during the three storms was entirely caused by the trees and shrubs.

Estimation of Aerodynamic Roughness Length

Lettau's model predicted a z_0 value of 26 mm in plot A. In plot B, this was only 6 mm because of the lower density of vegetation elements. Overall, the estimated values of z_0 are low. A z_0 value of 6 mm corresponds to roughness in a homogenous terrain of fallow ground,

Table I. Characteristics of selected storm events at field A and B, near Windou, north Burkina Faso

Date	Duration (min)	Wind speed at 3·25 m ($m\,s^{-1}$)				Wind direction at 3·25 m (°)				Sediment transport ($g\,m^{-1}\,s^{-1}$)			
		Average	Min	Max	σ	Average	Min	Max	σ	Average	Min	Max	σ
Site A													
27 May 03	28	9·6	4·1	15·1	2·7	110	55	171	33	26·9	6·4	42·9	11·2
26 June 03	18	12·5	9·7	15·6	2·0	54	46	62	5	31·3	3·4	73·6	19·6
01 July 03	26	9·7	7·3	13·1	1·5	113	97	125	6	8·5	0·9	17·1	5·7
Site B													
27 May 03	31	10·1	5·9	14·9	2·0	136	68	202	37	6·3	2·1	10·6	2·4
26 June 03	18	12·7	9·9	15·8	1·6	59	52	70	6	17·0	4·2	29·1	7·9
01 July 03	19	12·9	9·8	15·1	1·5	125	107	134	7	22·5	5·0	66·9	1·5

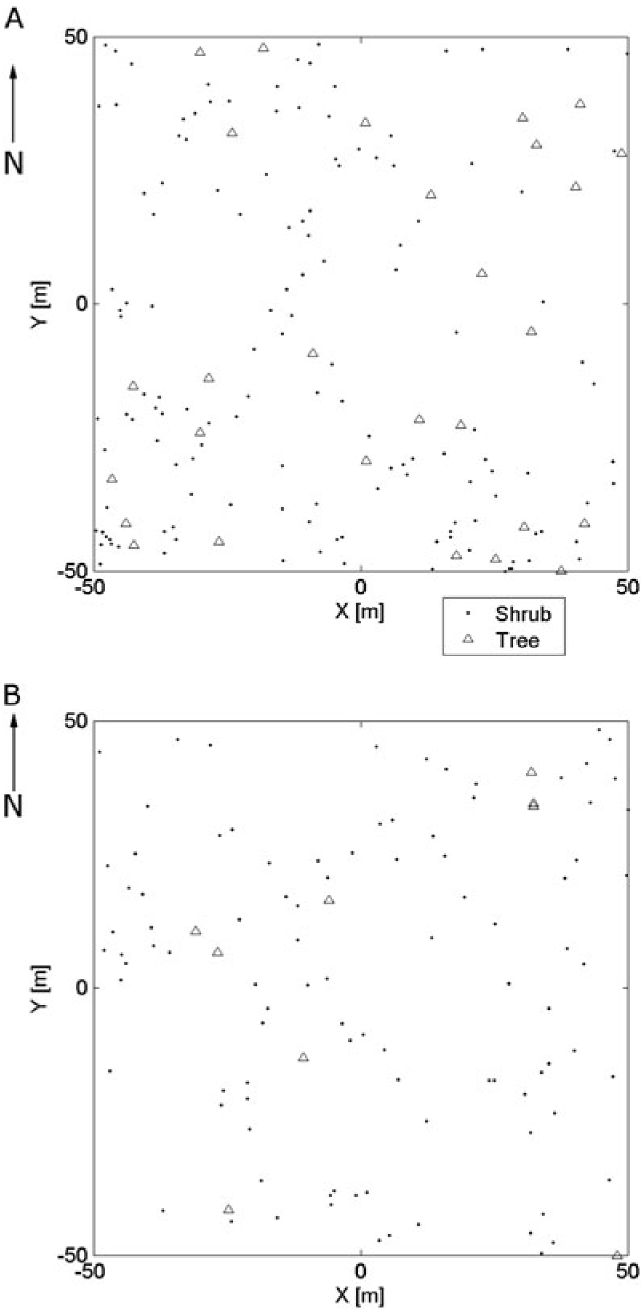

Figure 4. Location of vegetation elements in experimental plot A and B, in the Sahelian zone of Burkina Faso.

Table II. Characteristics of height (h), width (w) and porosity (θ) of vegetation elements in two experimental plots at two farmers' fields near Windou, north Burkina Faso

	A ($n = 129$)			B ($n = 70$)		
	h	w	θ	h	w	θ
Mean	1·84	2·74	0·56	1·61	1·62	0·58
Standard deviation	1·44	2·41	0·14	1·93	1·12	0·15
Skewness	1·08	1·52	0·33	3·24	2·12	−0·40
Min	0·50	0·39	0·26	0·61	0·63	0·28
Max	6·49	11·15	0·95	10·61	5·92	0·88

and a z_0 value of 26 mm corresponds to values found in long grass and heather (Wieringa, 1993). The low values of z_0 were attributed to the dispersed vegetation and the bare surface areas in between. The models of Lettau (1969) and Wieringa (1976) were applied to determine the effect of the present vegetation at both plots on wind speed compared with the situation when all woody vegetation would have been removed (bare plot). For this purpose, the z_0 value of an entirely bare plot was assumed equal to 0·5 mm. At a station height of 3·25 m at plot A, wind speed for a bare plot would have increased by 23·0% compared with the current situation. For experimental plot B, this was 11·1%. These increases in average wind speed can also be expressed as reductions in wind speed as a result of the vegetation cover. For plot A, this reduction was equal to 18·7% compared with a bare plot, and for plot B, the reduction was 10·0%. Hence, the cover of scattered, woody vegetation in both plots did slow down the undisturbed average wind speed during the storms.

At the local scale, the influence of the vegetation elements (shrubs and tree trunks) on wind speed was calculated for the events of 27 May, 26 June and 1 July. At field A, 32% of the area of the experimental plot was affected by the vegetation elements. At site B, this was only 11%. The average factor of change in wind speed (φ) in the areas where wind speed was affected was 0·48 at plot A and 0·49 at plot B. Because these areas comprised only a limited proportion of the total surface area in the plot, the average reduction factor for the entire plots is much higher. For plot A, the average reduction factor was 0·92, and for plot B, it was 0·98.

Prediction of Sediment Transport

The sediment transport modelling using Equation 1 of all three events showed more or less similar results. Figure 5 shows the calculated factor of sediment transport change (ψ) in the vicinity of the vegetation elements larger than 50 cm at both experimental plots for the event of 26 June. Obviously, the area that was affected by the presence of vegetation elements is the same as for the change in wind speed (32% at plot A and 11% at plot B). The modelled average factor of change in sediment transport (Ψ) at experimental plot A was 0.88, and for plot B, this was 0·98. This means that the local effect of vegetation elements at plot A involved a 12% reduction of sediment transport; at site B, this was only 2%.

Scenario Testing

Scenarios of different vegetation characteristics and densities were developed and run for the event of 26 June 2003 for the experimental plot of field B. This event was chosen because it was of short duration and had a high average wind speed (Table I). The results of the scenarios that were run are presented in Table III. The changes in wind speed and sediment transport are all relative to the measured wind speed

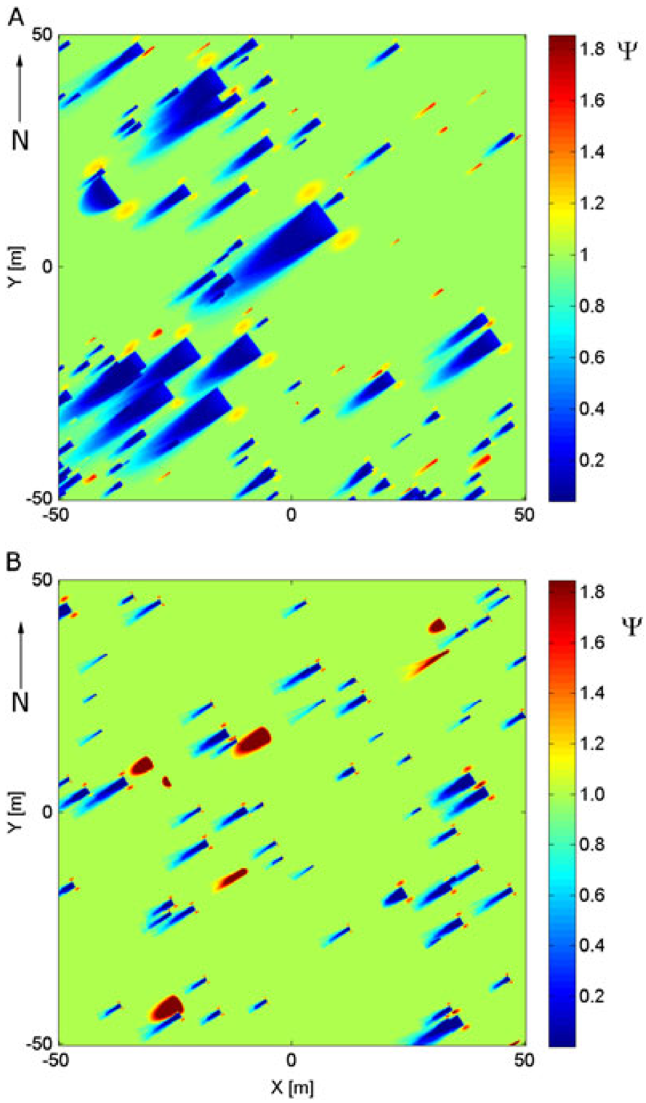

Figure 5. Modelled change in sediment transport (Ψ) in the vicinity of vegetation elements together with the location of 17 MWAC catchers on two experimental plots, for the storm event of 26 June 2003, north Burkina Faso. (A) Experimental plot at study site A and (B) experimental plot at study site B.

and modelled sediment transport in plot B, so with vegetation present. The change in wind speed and sediment transport was expressed with factors relative to the modelled results for the same event.

First, the effect of removing all vegetation from the area was calculated. This resulted in an increase of 175% in sediment transport compared with the actual situation in plot B (Table III). Hence, the impact of removing all vegetation in an area has large implications on the amount of wind erosion that can occur. Type I scenarios tested the effect of the average silhouette area of the vegetation elements present in the experimental plot. The height and width of the vegetation elements that were taken into account in the field situation were multiplied with a constant factor, first by 1·5 (50% increase in silhouette area) and then by 2·0 (100% increase in silhouette area). With increasing silhouette area, the net change in sediment transport (Ω) decreased exponentially. With type II scenarios, the effect of the number of vegetation elements was tested. The percentage of trees and the average characteristics of the vegetation elements stayed the same as in the actual field situation. The location of the vegetation elements in the plot was chosen randomly. In this scenario, Ω increased by 61% when the total number of vegetation elements was reduced to only 25. With an increase in vegetation elements, first to 50 and then 125, Ω seemed to reduce exponentially as well, although the exponential decline is less compared with type I scenarios.

Type III scenarios tested the effect of the ratio of tree-type vegetation elements to shrub-type vegetation elements. The number of vegetation elements in these scenarios is equal to the number of elements in the field situation (Table III). By increasing the percentage of trees, the silhouette area increased (Table III) and sediment transport decreased exponentially. Although, locally in the field, sediment transport is increased because of the increase of wind speed around the trunk of trees (Ψ_S is larger than 1 in scenario III-c, III-d and III-e), this effect seems insignificant when comparing it with the effect that these large vegetation elements exert on the sediment transport by affecting the wind speed for the entire field (Q_S). For example, for a tree percentage of 50%, the model calculated a small increase in the local sediment transport in the plot ($\Psi_S = 1{\cdot}03$). However, because of the reduction in the average wind speed ($U_S = 0{\cdot}83$), the amount of sediment transport in unobstructed flow decreased strongly ($Q_S = 0{\cdot}23$). The net effect of this scenario was a reduction of 76% ($\Omega = 0{\cdot}24$) in sediment transport compared with the actual field situation. Hence, the type III scenarios clearly indicate that the presence of trees is more important in influencing the sediment transport in an area than that of shrubs. Trees are large objects, and as a consequence, the higher the tree density, the larger the average silhouette area, which slows down the average wind speed in an area.

The last scenarios were run to test the effect of the spatial arrangement of vegetation elements in a field. It was evaluated whether vegetation elements that are evenly distributed in the field would result in a lower sediment transport compared with vegetation elements that are randomly scattered in the field. The number and size of trees and shrubs in scenario IV-a is similar to the actual field situation. Scenario IV-b is similar to scenario II-b, and scenario IV-c is similar to scenario II-c. The only difference is that in the type IV scenarios, the positions of the vegetation elements were randomly chosen and different from the positions in the actual field situation and the type II scenarios. The calculated changes in wind speed and sediment transport for the scenarios IV-a, IV-b, and IV-c are exactly the same as those of the field situation, scenario II-b and scenario II-c respectively. This indicates that there is no difference in the effect of spatial distribution when vegetation is evenly or randomly distributed, when considering scattered vegetation. This result is not surprising, as the

Table III. Results of scenarios that were run for the storm event of 26 June 2003 at study site B, in the north of Burkina Faso[a]

Scenario	Shrubs (n)	Trees (n)	$\overline{h}$ (m)	$\overline{w}$ (m)	$\overline{\theta}$ (–)	U_S (–)	Q_S (–)	Ψ_S (–)	Ω (–)
26 June 2003	61	9	1·61	1·62	0·58	1·00	1·00	1·00	1·00
0: No vegetation present	0	0	–	–	–	1·11	2·70	1·02	2·75
I-a: $\overline{h}$, $\overline{w}$ [a] 1·5	61	9	2·42	2·44	0·58	0·92	0·50	0·94	0·49
I-b: $\overline{h}$, $\overline{w}$ [a] 2	61	9	3·22	3·25	0·58	0·85	0·27	0·89	0·25
II-a: $n = 25$; $\overline{h}$, $\overline{w}$ = field situation	22	3	1·61	1·62	0·58	1·05	1·58	1·02	1·61
II-b: n = 50; $\overline{h}$, $\overline{w}$ = field situation	44	6	1·61	1·62	0·58	1·02	1·17	1·00	1·17
II-c: $n = 125$; $\overline{h}$, $\overline{w}$ = field situation	109	16	1·61	1·62	0·58	0·97	0·74	0·94	0·69
III-a: 0% trees	70	0	1·05	1·35	0·62	1·06	1·65	0·98	1·62
III-b: 7% trees	65	5	1·36	1·50	0·61	1·03	1·26	0·99	1·25
III-c: 30% trees	49	21	2·38	2·46	0·61	0·93	0·53	1·01	0·54
III-d: 50% trees	35	35	3·50	3·41	0·59	0·83	0·23	1·03	0·24
III-e: 100% trees	0	70	5·93	5·40	0·58	0·65	0·05	1·06	0·05
IV-a: $n = 70$, evenly distributed	61	9	1·61	1·62	0·58	1·00	1·00	1·00	1·00
IV-b: $n = 50$, evenly distributed	44	6	1·61	1·62	0·58	1·02	1·17	1·00	1·17
IV-c: $n = 125$, evenly distributed	109	16	1·61	1·62	0·58	0·97	0·74	0·94	0·69

[a] U_S is the factor of change in the average wind speed as a result of an alteration in aerodynamic roughness length.
Q_S expresses the change in sediment transport because of a change in average wind speed. ψ_S is the normalized change in sediment transport for each scenario and accounts for the local effects of the vegetation elements. It was calculated by dividing the average change in sediment transport (ψ_i) of each scenario (i) by the value of ψ of the event of 26 June 2003. Ω is the overall effect on sediment transport of a scenario, calculated by dividing the average amount of sediment transport that was modelled using the scenario with the average amount of sediment transport that was modelled for the event of 26 June 2003.

density in scattered vegetation is generally so low that obstacles act in isolation and wind speed reduction zones do not interfere much with each other (Figure 4B).

DISCUSSION

The developed model is capable of predicting wind speed reductions as a result of scattered, woody vegetation cover in an area, but the calculated reductions are relatively small. Kainkwa & Stigter (1994) measured wind speed reduction (at 2·5-m height) in a savannah woodland in Tanzania equal to ~50% for tree cover of 120 trees per ha and ~30% for tree cover of 60 trees per ha. Our plot A had a tree density of 28 trees per ha and reduced wind speed by 18·7% at 3·25-m height. For the same measurement height of 2·5 m, the estimated reduction in wind speed would be 20·7%. Given the lower tree density in plot A, the obtained reduction seems to be in agreement with the Kainkwa & Stigter (1994) results.

Unfortunately, Kainkwa & Stigter (1994) did not provide z_0 values for their plots. In this study, the model of Lettau (1969) was chosen to model z_0 values because of its simplicity and because it takes the effect of coverage, obstacle shape and height of the vegetation elements into account to calculate the z_0 value. This was considered as an advantage over other simple models that estimate the value of z_0 based on height alone. Wieringa (1993) stated that Lettau's model is limited up to moderately inhomogeneous situations, and its application in wake interference flow is not proven. However, according to Petersen (1997), Lettau's model provides a good estimate of the surface roughness length. Lloyd *et al.* (1992) compared the z_0 value calculated with Lettau's model with measurements in a sparsely vegetated plot in south Niger. The average of the measured z_0 values by Lloyd *et al.* (1992) was 0·153 m, while Lettau's model predicted a z_0 value of 0·145 m. This z_0 value is an order of magnitude larger than the z_0 values that were found in our study, which can be explained by the much higher vegetation cover in the Lloyd *et al.* (1992) study. Given the uncertainty in the predictions of Lettau's model for terrains with low vegetation cover, a first step in evaluating the presented model would be to test its validity for a range of sparsely vegetated terrains.

The patterns of wind speed reduction and changes in sediment transport as modelled in this study are similar to the modelled patterns obtained by Dupont *et al.* (2014). They developed a saltation model fully coupled with a large-eddy simulation airflow model and simulated wind flow and sediment transport for sparse vegetation cover on a sandy soil (median diameter = 200 µm). The numerical model provides much detail about momentum fluxes between the airflow and the surface with vegetation elements. The Dupont *et al.* (2014) model results confirm the earlier observations about the different effects of trees and shrubs on wind flow (Leenders *et al.* (2007). A shrub creates a wake zone in the lee of its canopy, while a tree creates a similar wake zone at the height of the canopy but also generates two zones of increased wind speeds around its trunk.

From the performed scenarios, two general features become clear. First, the scenarios showed that the local effect of trees and shrubs on sediment transport varied less than the effect that these vegetation elements exerted on sediment transport through affecting the average wind speed in an area (Table III). In the model, the vegetation elements in the tested scenarios altered the sediment transport in their vicinity (Ψ_S) up to 11% (scenario I-b). The effects on sediment transport as a result of the change in the average wind speed (Q_S) were much larger. This is illustrated with the results of the type III scenarios. In those scenarios, the number of vegetation elements remains equal, but the shrub/tree ratio changes. When there are zero trees in the area, the wind speed increases by 6%, but when all shrubs are replaced by trees, the wind speed reduces by 35% and the sediment transport by 95% (Table III).

According to the model, the local effects of vegetation elements are less than the large-scale effects, but it cannot be concluded that the local effects of vegetation elements on sediment transport are not important. Because of the local effects, the crop production might locally increase because of enrichment of the soil from sediment entrapment by shrubs (Sterk *et al.*, 2004). For a farmer, this is extremely important because the trapped sediments contain small amounts of nutrients that stimulate crop growth (Sterk *et al.*, 1996). However, the scenario runs indicate that the average sediment transport in a field is much more affected by the trees in the surrounding areas than by the vegetation elements that are actually present in the field. The sediment transport reduction that one can achieve at a field, by managing the natural woody vegetation present at this field, is thus limited. Therefore, a farmer who wants to diminish the sediment transport at his field(s) effectively has to ensure that large vegetation elements are present at areas upwind of his field(s). Because of the variable wind direction of storm events, the location of upwind fields differs. This means that for an effective reduction in sediment transport at one field, vegetation elements have to be present in fields surrounding this field. Therefore, using natural woody vegetation as a wind erosion control strategy involves collaboration between farmers and regeneration and management of woody vegetation at the scale of at least a village.

A second feature that can be deduced from the scenarios is that different combinations of vegetation characteristics and number of vegetation elements present in an area result in the same change of sediment transport. A decrease in the number of vegetation elements from 70 to 25 (scenario II-a) with both trees and shrubs present resulted in the same change in sediment transport as a situation in which no trees and 70 shrubs were present (scenario III-a). Thus, the combination of characteristics of vegetation elements in a field determines the amount of protection against aeolian sediment transport. Rather than one optimum, there is a range of combinations in silhouette area, type of vegetation elements (trees and shrubs) and the density of vegetation elements that determine the extent of change in sediment transport. The best reduction in sediment transport is obtained by a combination of a high density of woody vegetation, a high percentage of trees and a large silhouette area. However, it is obvious that a farmer is not easily willing or able to meet these criteria. For example, farmers might not want to have more than a certain number of vegetation elements within their fields because they fear competition for water, light and nutrients with the main crop. The reduction in sediment transport that is achievable in a certain situation is therefore also subject to boundary conditions inherent to the farming system and specific needs and interests of farmers.

Boffa (1999) has summarized many other benefits of scattered woody vegetation that can help to increase the vegetation cover in farmers' fields. These are harvestable and sometimes marketable by-products, such as food items (flowers, seeds, nuts, fruits and leaves), traditional medicine, fire wood, timber, and some specific products like gum Arabica from *A. tortilis* ssp. *raddiana* (Savi). Apart from wind reduction, trees and shrubs in agroforestry parklands can help to improve natural resource management and crop production by soil fertility improvements, microclimate changes and reduced surface run-off and water erosion. Better soil fertility in the immediate surroundings of trees and shrubs has been observed several times, but the reasons remain unclear. Recycling of litter, nitrogen fixation and trapping of atmospheric dust have all been postulated as possible reasons, but no conclusive evidence for any of those reasons has been provided so far.

The microclimate changes in agroforestry parklands result from reduced wind speeds and less solar radiation under canopies. These two effects result in lower soil evaporation and transpiration rates, increasing the moisture storage in the soil (Boffa, 1999). In a dry environment like the Sahel, a slight improvement in moisture storage during the crop season may have an important effect on the final yield. Especially near and under *F. albida* (Delile) A. Chev. trees, the crops usually perform better than in the open, which probably can be attributed to the combined effects of microclimate changes and better soil fertility. The canopies of trees and shrubs are also effective in the interception of high-intensity rainfall, thereby reducing crust formation under the canopies, which leads to better infiltration rates. Hence, the amounts of surface run-off and water erosion will also be reduced (Boffa, 1999).

Finally, by regenerating the natural woody vegetation in the Sahel, more carbon can be sequestered. If the regeneration projects would manage to achieve mature parklands covering their maximum range, carbon stocks in Sahelian productive land would be about 1284 Tg, which is nearly double the amount of a treeless scenario (~725 Tg; Luedeling & Neufeldt, 2012). Hence, a regreening of the Sahel with abundant tree and shrub cover could help to mitigate the global climate change.

CONCLUSIONS

Wind erosion is a major constraint to crop production in the Sahel, but adequate measures to control the erosion are generally lacking. Natural regeneration of woody vegetation has a potential to reduce wind speeds and sediment transport. The developed wind erosion model is well capable of quantifying the reductions in wind speed and sediment transport around shrubs (Leenders *et al*., 2011), but the newly developed submodel for the effects of trees on the wind flow needs more measured field data from sparsely vegetated areas to validate its results. However, the obtained model results are comparable with previously reported wind reductions in a savannah woodland in Tanzania (Kainkwa & Stigter, 1994).

The tested scenarios showed that trees are especially important to reduce wind speeds and wind erosion in an area. Because of their large height and crown sizes, trees increase the aerodynamic roughness of the terrain more than shrubs. Trees reduce the large-scale wind flow more strongly than shrubs, but shrubs are more effective in stabilizing the surface. Shrubs can trap material already in transport and protect the soil underneath the canopy and in the immediate lee downwind of the shrub. To fully exploit the wind erosion reduction capacity of natural woody vegetation in the Sahel, it is important to create tree-dominated landscapes and integrate shrubs in agricultural fields. Selection of appropriate tree and shrub species that reduce wind erosion, have minimal competition with crops, and can provide other beneficial effects and by-products remains a real challenge in the Sahel.

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