

The effect of vegetation patterns on wind-blown mass transport at the regional scale: A wind tunnel experiment

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ABSTRACT

Wind erosion is a global environmental problem. Re-vegetating land is a commonly used method to reduce the negative effects of wind erosion. However, there is limited knowledge on the effect of vegetation pattern on wind-blown mass transport. The objective of this study was to investigate the effect of vegetation pattern on this phenomenon within a land unit and at the border between land units. Wind tunnel experiments were conducted with artificial shrubs representing *Atriplex halimus*. Wind runs at a speed of 11 m s^{-1} were conducted and sand translocation was measured after 200–230 s using a graph paper prepared for this purpose.

This research showed that: 1) the transport within a land unit is affected by the neighboring land units and by the vegetation pattern within both the unit itself and the neighboring land units; 2) re-vegetation plans for degraded land can take into account the 'streets' effect (zones of erosion areas similar to streets); 3) the effect of neighboring land units includes sheltering effect and the regulation of sediment passing from one land unit to the neighboring land units and 4) in addition to investigation of the general effect of vegetation pattern on erosion and deposition within the region, it is important to investigate the redistribution of sediment at smaller scales depending on the scope of the project.

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1. Introduction

Many arid and semi-arid areas in the world suffer from the consequences of wind erosion (Cornelis, 2006; Stroosnijder, 2007). Airborne dust particles pollute the air and can cause health problems to the inhabitants (Thomas and Turkelboom, 2008), saltating grains can cause crop damage, and the removal of the topsoil reduces soil fertility, eventually resulting in degraded areas (Nanney et al., 1993). To minimize sediment transport and reduce the erosive forces of wind, re-vegetation of degraded land is a widely used approach (Leenders, 2006; Wang et al., 2011; Zhao et al., 2011). A minimal vegetation cover providing optimal protection against wind erosion reduces costly re-vegetation efforts and competition for limited water

resources. Leenders et al. (2007) indicated that the parkland system, in which a combination of trees and shrubs are distributed over an area, provides potential for regional scale protection against the negative impact of wind erosion. This study investigates the effect of vegetation and its pattern on the wind-blown sand transport.

A large number of studies have reported that vegetation has the capacity to decrease soil loss by wind as it reduces wind speed and soil erodibility, and increases the entrapment of eroded material (Van De Ven et al., 1989; Sterk et al., 1998; Udo and Takewaka, 2007; Abdourhamane Toure et al., 2011; Leenders et al., 2011; Munson et al., 2011). Research on stabilization of moving sand dunes has also linked reduction of sand movement to the increased trapping capacity of vegetation cover (Hesse et al., 2004; Chang et al., 2011; Drenova, 2011; Floyd and Gill, 2011). Lancaster and Baas (1998) showed that vegetation increases both the aerodynamic roughness length and the threshold wind shear velocity. Leenders et al. (2007), in their study of the effect of dispersed shrubs and trees on wind erosion in an agricultural field in the Sahel of Africa, showed that shrubs decrease the total mass flux by trapping soil particles and trees decrease the wind speed and, thus, erosive force. Therefore, for

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optimal protection of the soil surface in agricultural fields, a combination of shrubs and trees is recommended. Studies have also shown that attention should be given to the percentage of cover in order to prevent increased turbulence, which may lead to an increase in wind erosion (Sterk et al., 1998).

Knowledge about the effectiveness of vegetation in reducing wind-blown sediment transport is essential for designing approaches for re-vegetation of degraded land (King et al., 2005; Burri et al., 2011). However, research on the impact of vegetation on wind-blown sediment transport under field conditions alone is not sufficient as, under field conditions, the effect of vegetation cannot be isolated. Under such conditions it is affected by other factors such as soil properties, changes of vegetation during the measurement period, topography and soil surface conditions (Lopez et al., 1998). Thus, wind tunnel studies are a useful additional procedure for studying the relationship between vegetation and wind-blown sediment transport under controlled conditions (Gabriels et al., 1997; Cornelis and Gabriels, 2004).

Several wind tunnel experiments have been undertaken to improve understanding of the relationship between vegetation and wind erosion. These experiments used pieces of dead vegetation (Molina-Aiz et al., 2006), living vegetation (Burri et al., 2011), or artificial vegetation (Cornelis and Gabriels, 2005; Udo et al., 2008; Wuyts et al., 2008) as surrogates for real-world vegetation. These studies concluded that vegetation reduces the total wind-blown sediment transport and that the impact of vegetation on sediment transport changed with vegetation density and porosity. Udo and Takewaka (2007) concluded from their wind tunnel experiments that, in addition to the density, the height and flexibility of the vegetation are essential characteristics determining effectiveness in the reduction of wind-blown mass transport. The results of the wind tunnel study of Burri et al. (2011) showed an exponential decrease in mass flux with increasing vegetation cover, although with low vegetation cover (around 3%) an increase in the mass flux was observed. Li et al. (2008) simulated *Tamarix* spp shrubs growing in “Nabkha” dunes in a wind tunnel and observed sand transport around the simulated vegetation. They concluded that vegetation reduced air flow above the sand mounds, changed the wind profile upwind and downwind of the sand mound, and decreased the sand transport from the mound area. These studies have provided valuable insight; however have some limitations regarding scale.

To date, the majority of wind tunnel experiments regarding vegetation effects on wind-blown mass transport have focused on the simulation of field conditions at the plot or point scale (Musick et al., 1996; Udo and Takewaka, 2007; Li et al., 2008). These results are important for understanding the effect of vegetation on wind-blown mass transport at specific locations and the mechanisms by which the

vegetation reduces the total mass transport around the vegetation element. However, for understanding the effects of vegetation on wind erosion at a regional scale, the results of these studies are insufficient. In regions vulnerable to wind erosion, land management activities in one land unit may affect wind erosion processes in neighboring land units (Hupy, 2004; Leenders, 2006). Furthermore, erosion that occurs in one land unit affects the units located downwind. Todd et al. (2004), Fryrear et al. (1998) and Youssef et al. (2012) studied the effect on the maximum sediment transport and reported a gradual increase in the mass flux from bare land downwind from a non-erodible border. Therefore, to understand the effect of vegetation at the regional scale, it is vital to generate data representing processes taking place along the entire land unit and at transitions between land units.

The objective of this study is to provide further understanding of the effect of vegetation cover and different vegetation patterns on the change in mass flux of wind-blown sediment at the regional scale through wind tunnel experiments. The main research questions are: 1) what is the change in wind-blown sediment transport at borders between bare and vegetated land? 2) What is the effect of vegetation pattern on the translocation of wind-blown mass transport across arable fields? 3) How does the vegetation pattern affect the size and spatial distribution of areas with erosion or deposition along land units? Answers to these questions will be discussed in the current paper.

2. Material and methods

2.1. Wind tunnel

This study was conducted in the wind tunnel of the International Center for Eremology (ICE), Ghent University, Belgium. The dimensions of the wind tunnel are 12 m in length (8.5 m used in study), 1.2 m in width with an adjustable roof height up to 3.2 m (Gabriels et al., 1997; Cornelis and Gabriels, 2004). Wooden spires and roughness cubes were used to create a boundary layer of 0.6 m at the upwind border of the experimental section which is 6 m from the entrance of the working section of the wind tunnel (Cornelis and Gabriels, 2004). Wind speed was measured with vane probe-type anemometers (Gabriels et al., 1997) placed at $X=5.85$ m (measured from the entrance), and $Y=0.6$ m (measured from the wall of the working section) positioned at heights of 0.02, 0.13, 0.27, 0.38, 1.10 m (Fig. 1). Sediment was stored in a 2.5 m long by 0.5 m wide by 0.01 m deep tray. To create a roughness similar to that of sand, sandpaper was affixed to the 1.5 m in front of the tray and on the areas to its left and right (Fig. 1).

As sand is very sensitive to wind erosion (Chandler et al., 2005), it was chosen for use in the present experiments. Beach sand was collected from the beach of Ter Heijde, Den Haag, Netherlands, dried

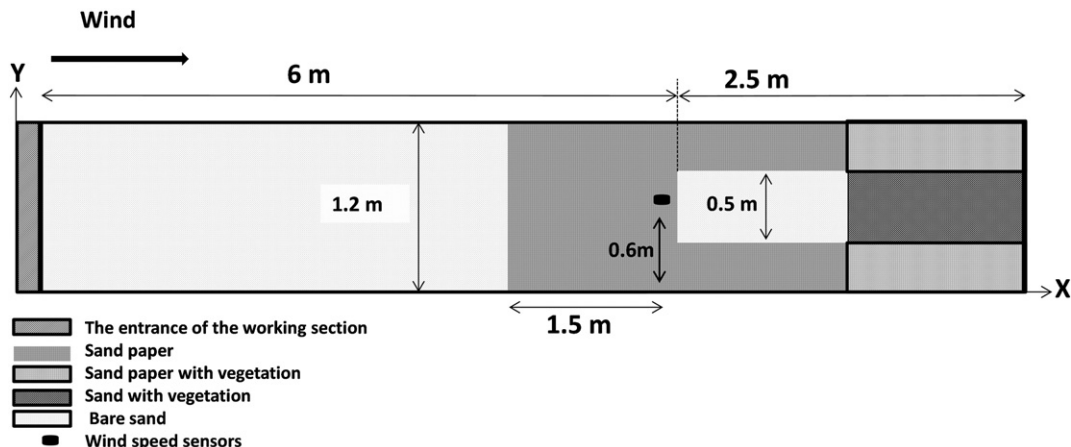


Fig. 1. The setup of the wind tunnel experiments at the ICE, Ghent Belgium.

for two weeks, and subsequently filtered through a 1 mm sieve to remove shells. Table 1 shows that more than 95% of the sediment particle size falls within the 100–500 μm range, which corresponds to the particle class that is highly vulnerable to wind erosion Chandler et al., 2005. The wind velocity during each run was 11 m s^{-1} at a height of 1.10 m above the (solid) sand paper and a distance of 6 m from the test section entrance. This corresponds to a shear velocity of 0.256 m s^{-1} determined following the procedure of Cornelis and Gabriels (2004).

2.2. Representation of vegetation

In arid and semiarid environments, *Atriplex halimus* is often used for re-vegetation of degraded land (Hassine and Lutts, 2010) because it has a low water requirement (less than 100–200 mm per year) (Martínez-Fernández and Walker, 2011). *A. halimus* also resists saline conditions and is survive heavy grazing (Ruiz-Mirazo and Robles, 2011). Therefore, in these experiments artificial plants with a morphology similar to *A. halimus* shrubs were used, applying a downscaling ratio of 1:50. This scale was chosen because it allowed accurate simulation of the height of *A. halimus* and distances between shrubs in real fields under the dimensional and boundary layer conditions of the wind tunnel. The modeled shrubs were between 2 and 2.5 cm high, representing 1 and 1.25 m-high *A. halimus* shrubs in the field (Fig. 2A). The shrub model consisted of polyethylene ribbons attached to iron sticks (Fig. 2B,C). Each shrub model has several sticks attached to each other at their lower end and fixed to a wooden board. The shrubs were then bent, to represent the shape of real *A. halimus*. The fraction of the surface covered by the vegetation was 10–11% throughout the experiment.

Wind-driven sediment transport was observed under two scenarios (Fig. 3). In the first scenario, the sediment movement from bare to vegetated land was simulated for four vegetation patterns. In the second scenario, the sediment movement from vegetated to bare land was simulated for one vegetation pattern. The patterns used (Fig. 3) were:

- 1) Pattern P.A: 36 individual modeled shrubs were positioned on a regular grid;
- 2) Pattern P.B: 32 individual modeled shrubs are placed in a sequence of offsetting the second, fourth, sixth and eighth rows of shrubs in the Y direction;
- 3) Pattern P.C: 18 patches (with two individual modeled shrubs for each patch) were distributed along the tray with rows of three patches perpendicular to the wind direction;
- 4) Pattern P.D: 12 patches (with three individual modeled shrubs for each patch) were distributed along the tray with rows of two patches perpendicular to the wind direction;
- 5) Pattern P.E: movement of sediment from vegetated to bare land was tested using shrubs in a regular grid shape.

A decrease in the number of shrubs was compensated for by an increase in the width of a single shrub, and thus, the fraction of surface covered by vegetation remained the same for all patterns (Fig. 3).

An average free-stream wind speed of 11 m s^{-1} (or shear velocity of 0.26 m s^{-1} above the surface) was chosen for all experiments. This wind speed provided movement of sand however did not affect the shape of the modeled vegetation in the wind tunnel. Before each run, the surface in the tray was smoothed using a soft brush to create a

homogenous sand height of 0.01 m. Each test lasted 200–230 s (except run 3 in P.D pattern) by which time all sand in the bare (upwind) part of the tray was eroded in patterns P.A, P.B, P.C and P.D. We ran three replicates for each pattern.

To measure the sand height along the experimental tray a $0.5 \times 0.25 \text{ m}$ piece of 0.3 mm thick graph paper (coated to prevent destruction from the sand) was used. The graph paper was inserted carefully into the pre-wetted sand, perpendicular to the wind direction, and the sand topography was drawn onto the paper. Pre-wetting the sand after each run prevented the surface from collapsing when inserting the graph paper. The height of the sand was first traced onto the graph paper, with the heights then read directly from the paper at 1 cm intervals resulting in 51 heights being recorded for each position of the paper in the tray. Fig. 3 shows the positions at which the sand heights were measured relative to the position of vegetation elements. This measurement scheme resulted in 1275 measurement points for each run of patterns P.A and P.B, 816 for each run of patterns P.C and P.D and 1887 for each run of pattern P.E.

Geostatistical interpolation of the data was performed using a spherical variogram model (which best fitted the data), and maps showing the spatial variation of sand heights along the tray were created by ordinary point kriging (Chappell and Warren, 2003).

2.3. Key simulated parameters of turbulence and saltation with the existence of vegetation

The simulation of wind-blown sediment in a wind tunnel is complicated because the parameters that affect the saltation process need to be either correctly represented or downscaled (White, 1996). Table 2 gives an overview of the key parameters affecting this study. We took these into consideration as follows:

- 1) The boundary layer and other aerodynamic criteria. Gabriels et al. (1997) showed that the boundary layer thickness of the ICE can be adjusted using wooden spires and roughness cubes. The boundary layer in this research was 0.7 m, which agrees with the boundary layer explained by White (1996). All other aerodynamic criteria for air flow were simulated correctly in the ICE wind tunnel (Gabriels et al., 1997; Dierickx et al., 2001).
- 2) The obstacle height, H : this parameter was downscaled by a ratio of 1:50. As noted, this scale was chosen because it allowed simulation of the height of *A. halimus* and distance between shrubs in fields under the dimensional conditions of the boundary layer of the wind tunnel (the maximum height of simulated shrubs was 2.5 cm).
- 3) The roughness length, Z_0 : to create roughness similar to sand on the floor of the wind tunnel, sand paper was affixed to the upwind area and sides of the sediment tray.
- 4) Particle diameter, D_p : According to White (1996), when simulating an obstacle 1 m in height, the particle diameter for simulation of sediment movements around the obstacle should be around $10 \mu\text{m}$. This means that a correct simulation for this parameter is not possible because, due to the cohesive forces that connect particles of small size, particles with a $10 \mu\text{m}$ diameter will not be saltated (White, 1996). Thus, we applied the downscaling ratio of 1:1 for the D_p parameter to ensure that the saltation process would take place.
- 5) The reference height, h , of measured wind speed: In this research the boundary layer was arranged to be 0.7 m and the wind speed was measured at heights of 0.02, 0.13, 0.27, and 0.38. Thus, the wind speed was measured within logarithmic portions of the wind tunnel (White, 1996). In addition, the free wind speed (above boundary layer) at a height of 1.10 m was measured for reference purpose (Gabriels et al., 1997).
- 6) The ratio of obstacle height to boundary layer (H/B_0): According to White (1996) if the ratio (H/B_0) for real field conditions is less

Table 1
Particle size distribution of the sediment used in the wind tunnel experiment.

Fraction (μm)	<50	50–100	100–300	300–500	500–1000
Percentage (%)	0.08	1.28	20.54	75.33	3.17

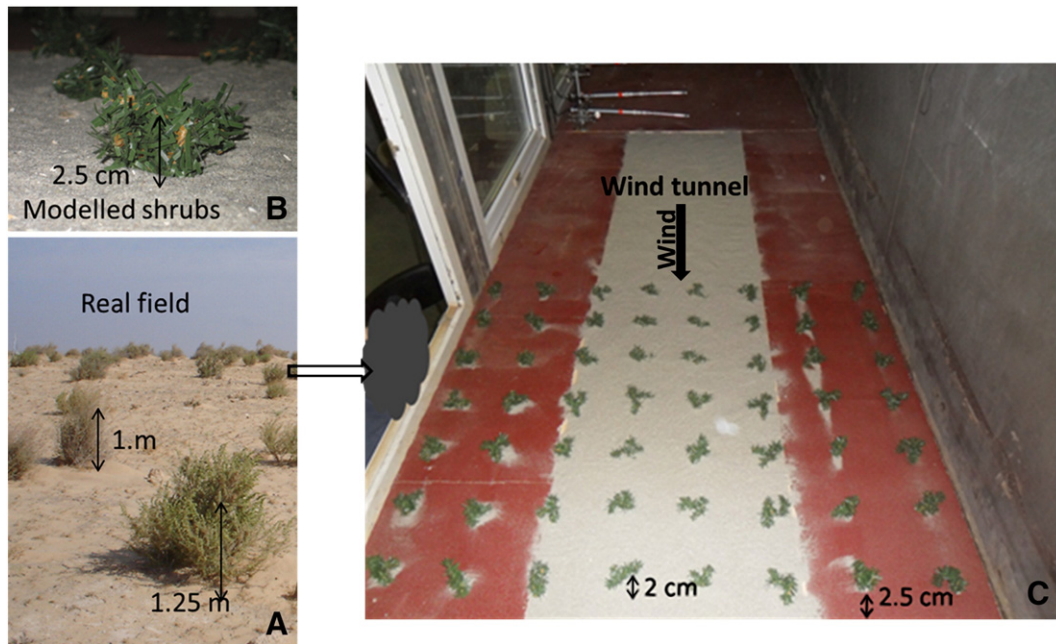


Fig. 2. View of *Atriplex* shrubs in the field (A), simulated shrubs in the tray (B) and in the wind tunnel (C).

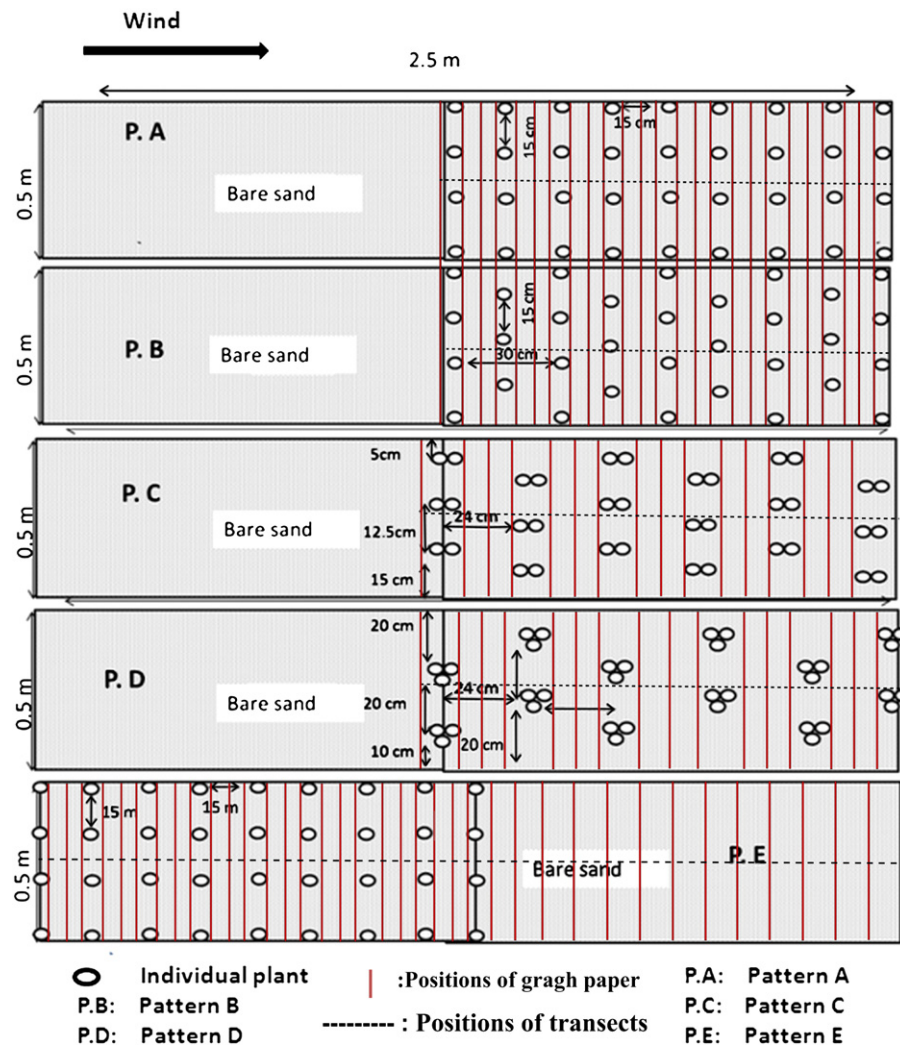


Fig. 3. Layout and vegetation patterns tested in the wind tunnel experiments.

Table 2
Parameters of saltation and flow simulated in this research.

Parameter(s)	Importance of scaling and simulation principles
Aerodynamic criteria and boundary layer (B_0)	Affect 1) the mean velocity and turbulence density and energy 2) roughness Reynolds number (R_{er}) 3) Jense length-scale criterion (Jensen, 1958) 4) the ratio (H/B_0) (White, 1996)
Obstacle height H :	The height should be under the dimensional conditions of the boundary layer (White, 1996)
Roughness length Z_0	Should be scaled exactly like field conditions to ensure $R_{er} > 2.5$ (White, 1996)
Particle diameter D_p	Affect gravity, drag, Saffman and Magnus forces that are essential forces in saltation process (Zou et al., 2007)
Reference height h	The height where wind speeds are measured should be within the logarithmic portions of the wind tunnel.
The ratio of obstacle height to boundary layer (H/B_0)	In aeolian saltation, the ratio (H/B_0) is less than 0.2 (White, 1996). And thus, that should be considered when simulate the field conditions.
Time scale T	Generally simulated saltation time is shorter than the time of saltation at real field conditions.

than 0.2 (which is the case for our study, the ratio for the wind tunnel should also be less than 0.2. In our simulation the maximum value of the ratio (H/B_0) was 0.035. Although in general terms the simulation here obeys the requirements of downscaling as suggested by White (1996) ($0.035 < 0.2$), the magnitude of the simulated and suggested values is quite different.

- 7) Time scale T : White (1996) showed that the time effect in wind tunnel experiments is much shorter than under real field conditions, and that the necessary duration of experiments is proportional to the wind velocity applied. In our simulation, the time applied was (200–230 s) at the wind speed of 11 m s^{-1} . This period was sufficient to empty the majority of the sediment reservoir.

3. Results

3.1. Spatial distribution along the experimental tray

For each of patterns P.A, P.B, P.C and P.D, the spatial distribution of sand height along the tray was similar for runs 2 and 3 (Table 3). Based on the divergent standard deviations (σ) and the variation in pattern, run 1 can be considered as a preparation run. The difference between the results of run 1 and runs 2 and 3 can be explained by the probable change in trapping efficiency after a vegetation element has trapped some sediment. After run 1, although the shrubs were cleaned using a soft brush to remove the sand around them, part of the sand among the small leaves was not completely removed.

For pattern P.E, since no incoming sediment was simulated from the upwind border the spatial distribution of sand height along the tray was similar for runs 1 and 2. Run 3 was removed from the calculations because sand removed during runs 1 and 2 was not completely replaced before run 3. That was due to the difficulty of adding sand between the leaves of the model shrubs. This condition resulted in a large variation in the patterns of erosion and deposition between run 3 and both runs 1 and 2.

The spatial distribution of sand height, averaged over runs 2 and 3 for each bare sand to vegetation scenario and over runs 1 and 2 for the vegetation to bare sand scenario, is shown in Fig. 4. As the sand height along the tray was 1 cm before the test, values above 1 cm represent deposition and values below 1 cm represent erosion. The first 125 cm of the tray is not included for the bare sand to vegetation patterns as this part of the tray was empty after each run.

With pattern P.A, deposition occurred behind shrubs. The amount of deposition decreased from the upwind border to the downwind border of the vegetated unit. In the area between rows parallel to the wind direction, erosion occurred with a gradual increase in erosion towards the downwind border. These result are in the agreement with the field research findings of Bowker et al. (2008), who found similar 'streets' of erosion in the downwind direction between shrubs for several dust storms in the north Chihuahuan desert. In pattern P.B, high deposition behind shrubs was observed in the upwind half of the tray. From the fifth (perpendicular to wind direction) row of shrubs to the end of the tray, decreased deposition and some erosion was recorded.

For patterns P.C and P.D, erosion was dominant, although low levels of deposition were observed behind the vegetated patches. Pattern P.E shows distinct erosion features at the upwind border of the tray. After the third row of shrubs there was a gradual increase in the deposition up to the end of the vegetated part of the tray. In the bare part of the plot, erosion started at a distance of 5–10 cm, which is equal to approximately 2–5 times the height of the vegetation elements.

The average σ for patterns P.A and P.B (0.21 cm, 0.20 cm) is higher than the σ for P.C and P.D (0.15 cm, 0.11 cm). Therefore, the patterns with lower numbers of vegetation elements (P.C and P.D) resulted in a more homogenous (gentler topography) surface than patterns with a larger number of vegetation elements (P.A and P.B).

3.2. Average sediment height for the tested area

To evaluate the general trend in erosion or deposition in the direction of the wind, transects parallel to the wind direction were calculated. For every 5 cm the mean of all sand heights was calculated and plotted (Fig. 5). As in Fig. 4, the first 125 cm is not included for patterns P.A, P.B, P.C and P.D, as this part of the tray was almost empty after each run.

Fig. 5 shows that, for each of patterns P.A, P.B, P.C and P.D, run 2 and run 3 gave comparable results, and that there are clear, consistent differences between the patterns. The minor differences can be attributed to the fluctuation of the wind speed during the runs.

Both patterns P.A and P.B show a small strip of erosion at the border between the bare and vegetated parts of the tray. As the shear velocity of the wind is reduced because of the presence of shrubs, mass transport rates decline as well (compared to the larger transport rates that blew away all the sand from the upwind part of the tray).

Table 3
Average sand height and standard deviation (σ) for each run ($r1$, $r2$ or $r3$) and vegetation pattern.

Pattern	P.A			P.B			P.C			P.D		
Run	$r1$	$r2$	$r3$	$r1$	$r2$	$r3$	$r1$	$r2$	$r3$	$r1$	$r2$	$r3$
Height	1.25	1.36	1.37	1.01	1.35	1.31	0.95	0.78	0.78	0.97	1.08	0.85
σ	0.16	0.21	0.21	0.15	0.21	0.18	0.15	0.16	0.13	0.14	0.11	0.11
Average* (σ)	0.21			0.20			0.15			0.11		

*The average (σ) is calculated from runs 2 and 3, because run1 is considered to be a preparation run.

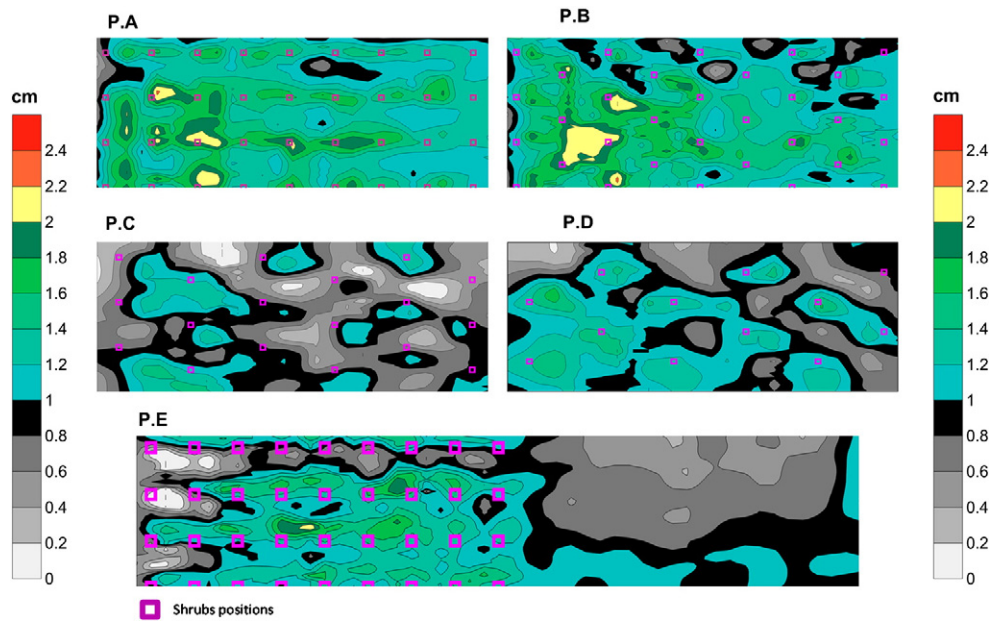


Fig. 4. Spatial distribution of sediment height over the tray for the average (calculated as explained in Section 3.1 of the results section) of 2 runs for each vegetation pattern.

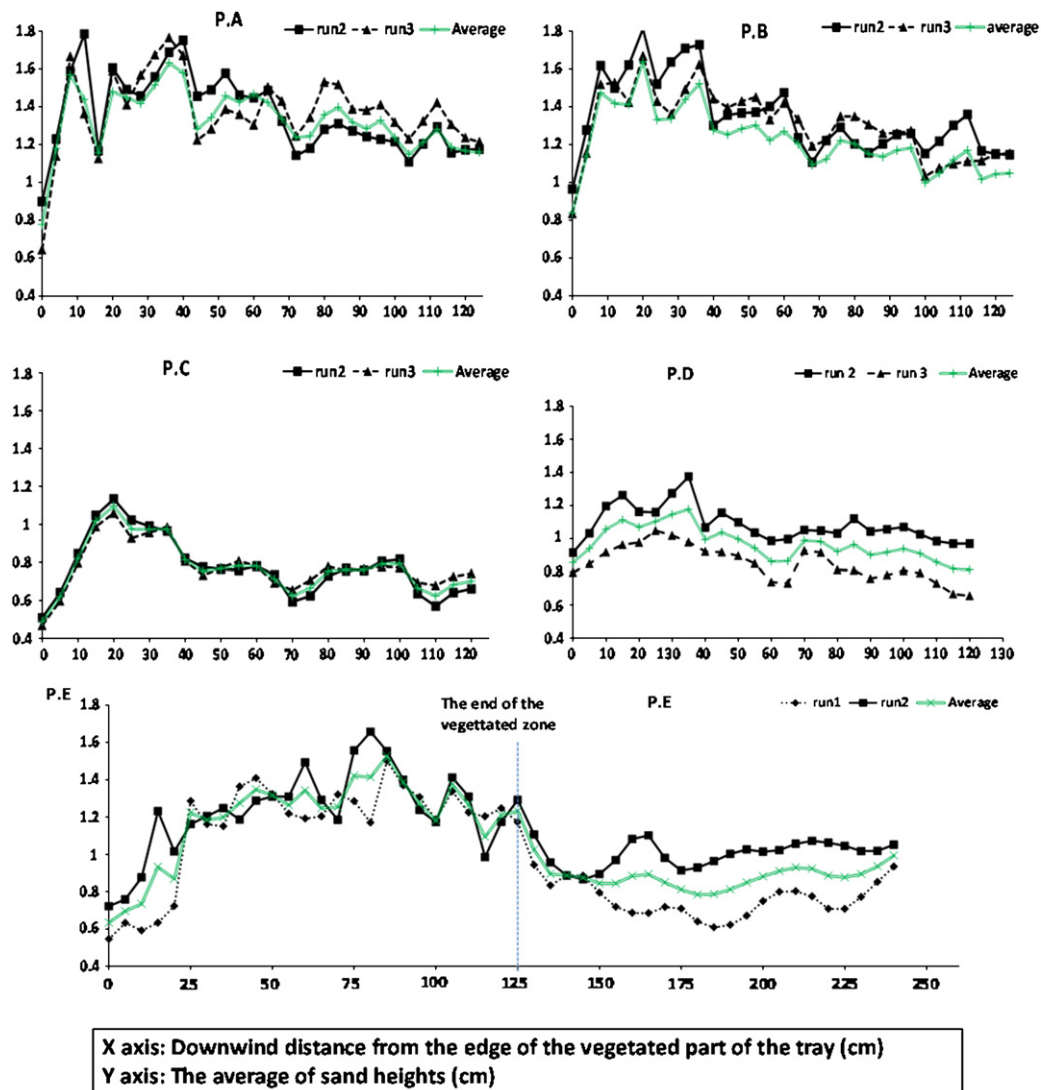


Fig. 5. Average sand heights along the downwind distance for runs 2 and 3 of each vegetation pattern.

Net deposition occurs from just 2.5 to 120 cm downwind from the vegetation edge. The initially high and then downwind-decreasing deposition indicates a decrease in sediment concentration due to decreased sand supply since much of the sand was entrapped by the upwind vegetation. Deposition reaches the highest level by 20 cm downwind from the border. Beyond this, deposition decreases gradually and trends toward equilibrium (neither erosion nor deposition) after 100 cm from the border.

In contrast to patterns P.A and P.B, pattern P.C resulted in net erosion continuing downwind for the entire length of the vegetation zone. The more sparsely distributed shrubs likely provided less frictional resistance, which would allow shear velocity to remain high, resulting in higher erosion rates. The continued erosion in pattern P.C along the first 15 cm from the vegetation edge indicates that the vegetation elements were too sparse to protect the area from erosion, even though the percentage of surface cover was similar to that of patterns P.A and P.B.

In pattern P.D, sand heights for runs 2 and 3 deviated on average 0.23 cm (Table 3) but the same general pattern was observed. The difference is probably due to the difference in the duration of the wind speed above 10.5 m s^{-1} between the two runs – 216 s for run 2 and 306 s for run 3. With longer duration a higher amount of sediment is eroded. Also in this pattern both runs still show erosion in the first 10 cm after the border, after which deposition occurs in run 2 and less erosion occurs in run 3. At the distance of 50 cm downwind from the vegetation edge, the airflow of run 2 appears to reach an equilibrium with no further significant erosion or deposition observed to the end of the tray. The results of run 3 show an increase in erosion from 35 cm up to 65 cm, followed by a decrease in erosion between 65 cm and 85 cm. From 85 cm to the end of the tray erosion again increased.

In the vegetated part of pattern P.E (vegetation to bare sand scenario), net deposition begins 10–20 cm from the border of the vegetated field. As observed in P.A, which had a similar vegetation pattern, the shrubs resulted in reduced shear velocity, and hence reduced erosion compared to a bare field. However, there was no compensation for the erosion that did occur, as was the case in P.A., because there was no sediment source upwind of the vegetated unit in the P.E setup.

3.3. Sand height with distance along a longitudinal transect at $Y=0.6 \text{ m}$

For more details on the sand height distribution along the tray, a 1 cm wide (Y direction) transect for sand heights along the middle of the tray ($Y=0.6 \text{ m}$, middle of the wind tunnel) was calculated using the average of two replications for each pattern (Fig. 6).

Fig. 6 shows that with patterns P.A and P.B, after a small strip of net erosion at the upwind border, net deposition can be observed the entire length of the tray. With pattern P.C, two small zones of net deposition occur at distances of 30 to 45 cm and 80 to 90 cm. Outside of these zones, net erosion was observed along the transect for pattern P.C. In the case of the P.D pattern, in the first 45 cm deposition was dominant, after which distance associated with net erosion is almost equal to that associated with net deposition. With pattern P.E, net erosion in the first 15 cm was generally followed by net deposition within the vegetated area, whereas net erosion was dominant within the bare sand area.

3.4. Erosion and deposition along the tested area

In the framework of land protection projects, the full impact of erosion or deposition must be known in order to choose a suitable vegetation pattern. And thus, it is not only important to know the general trend of erosion or deposition along a land unit with certain vegetation characteristics, it is also essential to know the size of areas associated with erosion or deposition and the severity of the erosion

or deposition within the region. To gain insight into the intensity of the mass transport effects, sand height was classified into five classes indicating the severity of erosion or deposition (Table 4). Fig. 7 shows the results of applying this classification for the average of two replicates for each vegetation pattern. It should be noticed that only the vegetated part of the tray was analyzed.

Fig. 7 shows that although a large percentage of cells were associated with deposition for patterns P.A and P.B, erosion also occurred at a small scale within these patterns. It should be noticed that in P.A., despite the potential risk of the corridor ('street') effect, erosion was observed in just 4.5% of the cells, whereas in P.B erosion was observed in 8.2% of the cells. In pattern P.C erosion was quite high accounting for 56.3% of the cells, whereas in pattern P.D erosion was lower (37.8%) and deposition was higher (34.7%) (comparing with the erosion and deposition percentage in P.C pattern). Although P.E has the same vegetation pattern as P.A, the percentage of cells associated with erosion was quite higher in P.E (26.4%) than in P.A (4.5%).

4. Discussion

4.1. Large-scale considerations

The effect of borders between different land units on the wind-driven mass flux is essential for understanding regional scale wind erosion. The variability of wind-blown mass flux found in this study in bare and vegetated fields along the dominant wind direction identifies a significant concept related to the border effect:

4.2. Sediment transport between bare and vegetated land units

According to the theory of Fryrear et al. (1998), when sediment travels over a bare land unit, it is expected that the absolute maximum transport is reached after a certain distance under the condition that the field length is not limited. When crossing a border with vegetation, the theory states that deposition occurs until a new transport process is started. In fact the vegetation causes a decrease in sediment concentration downwind from the vegetation edge because it traps a significant amount of the moving sediment. Patterns P.A, P.B and run 2 for pattern P.D show results that are in agreement with this theory. A sediment-laden air flow reaches the border of vegetation, after which deposition occurs and at the end equilibrium is established. Although for patterns P.A. and P.B equilibrium was not fully reached, the trend clearly shows decreasing deposition. This result is also in agreement with the findings of Chen et al. (1995), Gash (1986), Irvine et al. (1997) and Wuyts et al. (2008) who reported that both the effect of vegetation on reducing wind speed and the trapping capacity of the vegetation increase inside the vegetated area from the upwind borders.

The results obtained with pattern P.C and run 3 of P.D are not in agreement with the theory. With the P.C pattern, sediment transport within the vegetated area is higher than within the bare area (Fig. 8). And for pattern P.D, while in run 2 the pattern and % cover were sufficient to reach an equilibrium between erosion and deposition, in run 3 (higher average wind speed) more erosion occurred. Several previous studies have indicated that limited surface cover (5–7.5%) combined with a certain minimum wind speed can increase wind-blown mass fluxes (Raupach, 1990; Raupach, 1992; Raupach et al., 1993; Michels et al., 1995; Sterk et al., 1998; Maurer et al., 2009) due to the increased turbulence caused by the limited vegetation cover. The effect of the wind speed on the increased mass flux is illustrated in the difference between runs 2 and 3 for pattern P.D. However, these studies did not mention the effect of the spatial distribution of the vegetative cover. Although the vegetative coverage was the same (11%) for all patterns, pattern P.C clearly showed an increase in mass transport, and with a higher average wind speed run 3 for pattern P.D also showed this increase in mass transport. These results lead to the

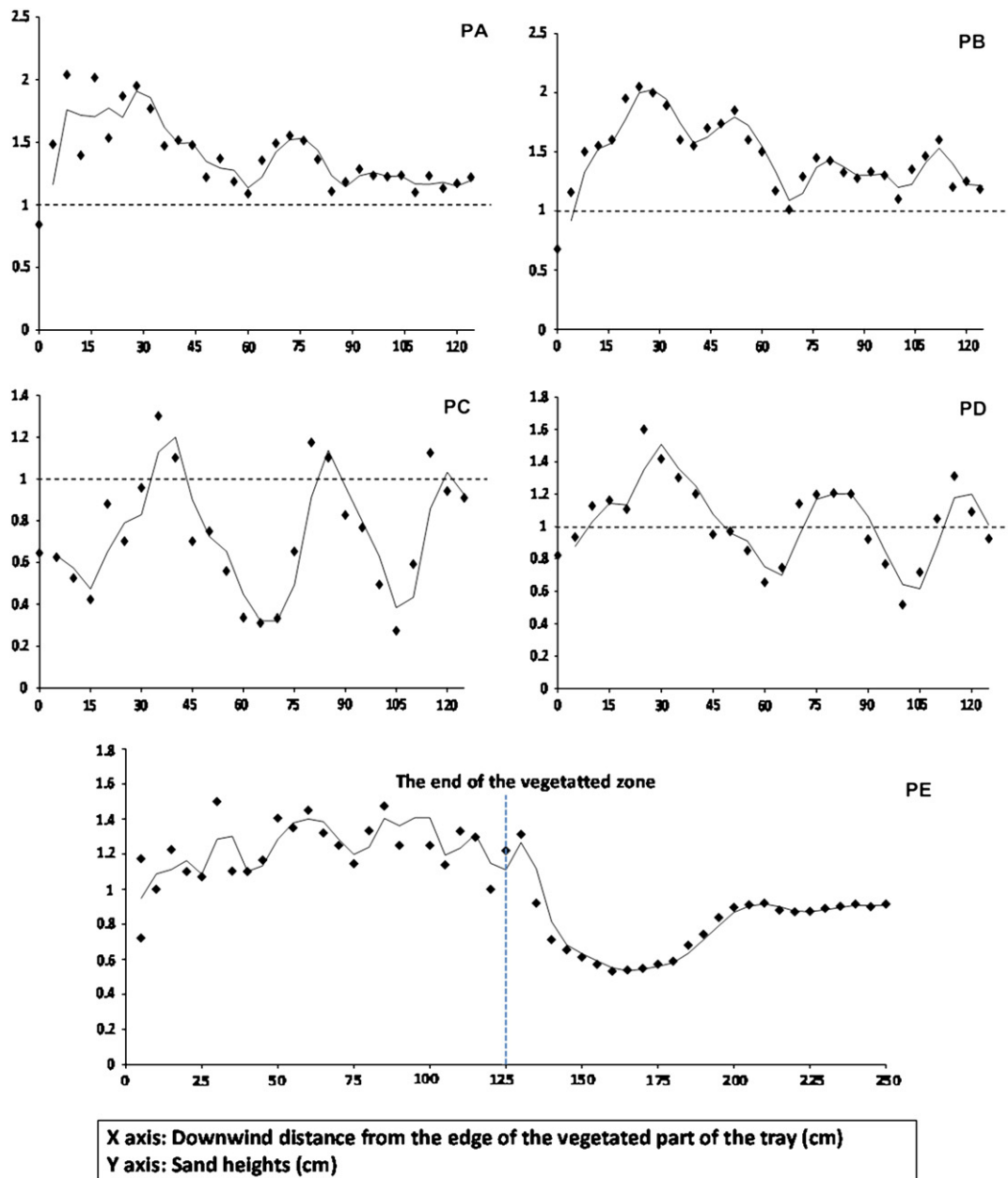


Fig. 6. Transect of sand heights along the downwind distance (average of two replicates).

conclusion that vegetation pattern is another factor that can cause an increase in the wind-blown mass flux, most probably due to an increase in turbulence. Therefore, in a region with a given cover, scattered patches of vegetation may exacerbate wind erosion especially under high wind speeds.

Table 4

Classification of erosion and deposition upon sand heights.

Sand height	0–0.45 cm	0.45–0.9 cm	0.9–1.1 cm	1.1–1.8 cm	1.8–2.5 cm
Explanation	Intense erosion	Erosion	Balance	Deposition	Intense deposition
Symbol	I E	E	B	D	I D

4.3. Small-scale considerations

Not only is regional scale investigation of the effect of vegetation pattern on general erosion or deposition important, investigation into the effects at small scales is also needed. In this study, none of the vegetation patterns protected the sediment surface sufficiently to completely halt wind-driven mass transport. The small-scale effects of vegetation found in this study are:

- 'Street' effect:** This effect refers to the formation of zones of erosion similar to streets. This effect was apparent in the P.A pattern where rows of vegetation were parallel to wind direction. In their research, [Bowker et al. \(2008\)](#) reported similar 'streets' of erosion in the downwind direction between shrubs for several dust storms in the north Chihuahuan desert. This effect should be taken into account when designing re-vegetation projects. Thus, if

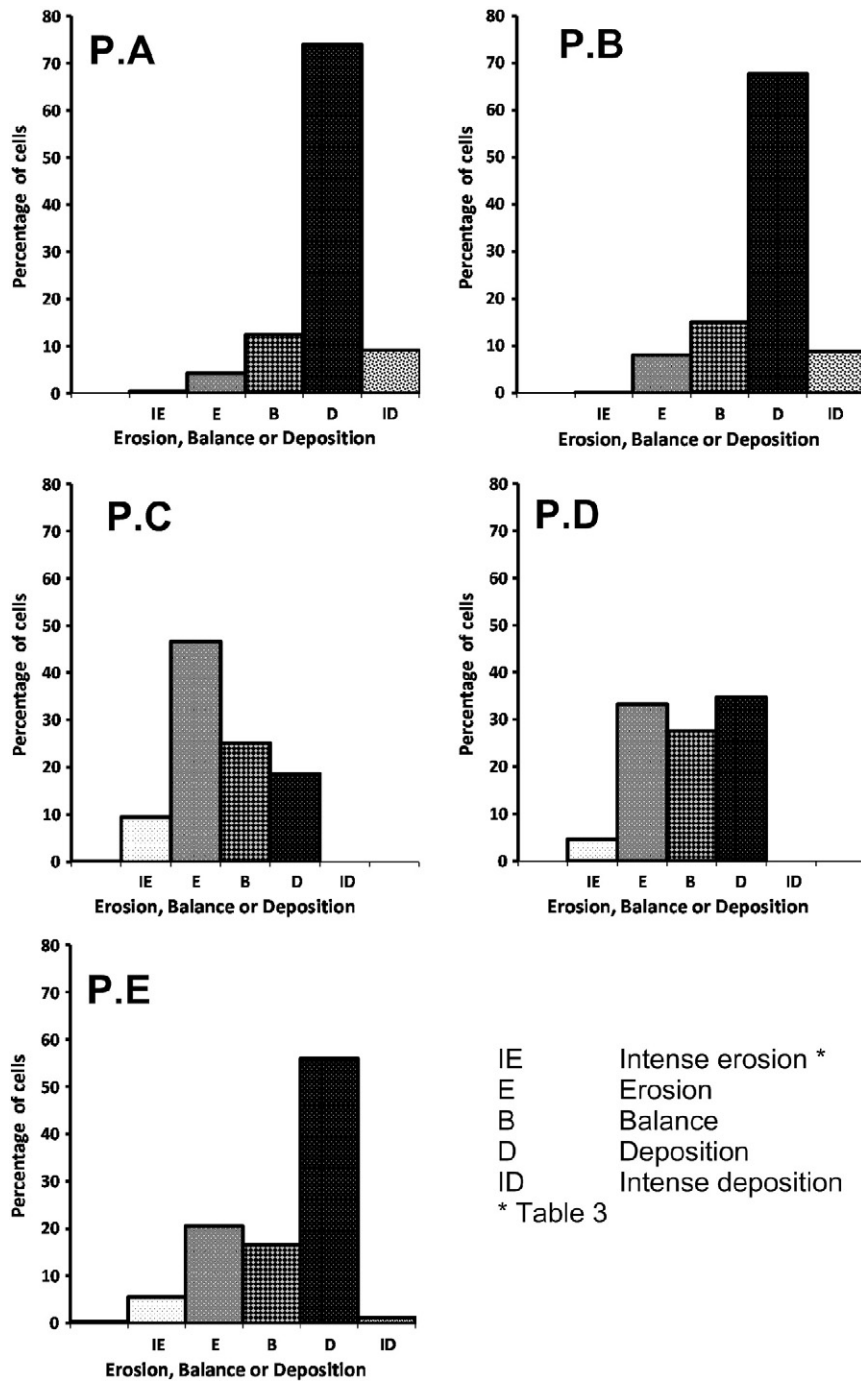


Fig. 7. Percentage of cells (1 pixel is 4 cm × 1 cm) with erosion, balance, or deposition along the tray for the average of three replications. Where *IE*, intense erosion; *E*, erosion; *B*, balance; *D*, deposition and *ID*, intense deposition (per Table 4).

the aim of the project is to prevent sediment from reaching a certain area, pattern P.B might be a more effective pattern than P.A. However, if the aim is to reduce sediment movement along the entire region, pattern P.A can be used. Therefore, taking into account the dominant wind direction, the vegetation pattern of rows of shrubs or trees may result in erosion zones similar to the shape of streets. This allows part of the sediment to reach the protected area, but the total sediment movement is reduced.

- b) *The spatial sequence of erosion and deposition.* Although over all, patterns P.C and P.D are mainly associated with erosion, the transects illustrated in Fig. 6 show that a spatial sequencing of erosion and deposition can occur – rather than just one or the other. Deposition can be linked to the redistribution of sand on

both sides of vegetation ‘elements’ in the Y direction perpendicular to wind direction. This small-scale deposition is not clear and can be neglected when considering things at the regional scale. However, when the focus of the protection project is involves the effect of wind-blown mass flux at the micro-scale, these zones of erosion and deposition may carry specific importance.

- c) *Sheltering zone.* The small sheltering zone of one land unit on a neighboring land unit, i.e. the sheltering effect of wind breaks, has been determined by several studies to be 10–20 times the height of the vegetation (Skidmore and Hagen, 1977; Heisler and Dewalle, 1988; Cornelis and Gabriels, 2005). In this study, the size of protection zone shows that the shelter-effect of one land unit on a neighboring land unit is similar to the effect of wind

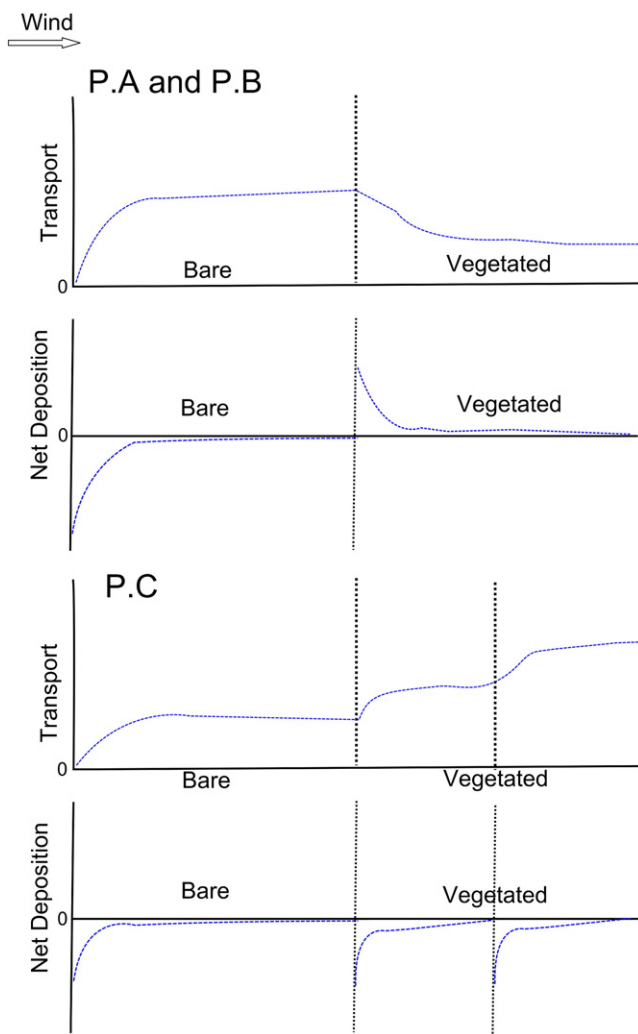


Fig. 8. Transport and deposition scheme for bare and vegetated land units.

breaks. And thus, the findings of this study support these earlier findings. This can be seen clearly in the P.E pattern, where the height of vegetation used is 2–2.5 cm and the sheltered area is 20–25 cm (Fig. 5). This explains why a zone of deposition was observed directly behind the border of vegetated area within the bare area in the P.E pattern (Fig. 5).

4.4. Size of areas associated with erosion or deposition

Depending on the aim of the re-vegetation project, the size of the area with net erosion or net deposition should be considered. Especially when protecting settlements, the exact distribution of sediment can be very important. Our results from testing the four vegetation pattern scenarios show that patterns P.A, P.B and P.E are characterized by deposition, pattern P.C is characterized by erosion, and P.D is mainly characterized by a net balance.

The number of vegetation elements per area appears to play a role in overall effect. The higher number of vegetation ‘elements’ in pattern P.C (18) compared to pattern P.B (32) resulted in a decrease in the percentage of cells with erosion from 56.3% in P.C to 8.2% in P.B. These results agree with Leenders et al. (2007) and Bowker et al. (2006, 2007) who concluded that, after wind events, deposition behind each individual vegetation element was observed. Thus, a higher number of vegetation elements results in a higher deposition rate. However our study also showed that an increase in the number of vegetation elements — from 12 in P.D to 18 in P.C — can result in an

increase in the percentage of cells with erosion from 34.7% in P.D to around 56.2% in P.C. And this indicated that certain vegetation pattern caused increase in the erosion from certain area.

Moreover, the ‘depositional with limited erosion’ patterns (P.A and P.B) and ‘erosional with limited deposition’ pattern (P.C) is a significant finding and should be taken into account when deciding which vegetation pattern to use for re-vegetating degraded land.

The higher percentage of cells with erosion in pattern P.E (26.4%) compared to pattern P.A (around 5%), is an important indicator of border effects. Thus, in pattern P.E, the vegetated part of the tray faced the wind first and thus no incoming sediment was simulated, while in the P.A pattern the wind first blew over the bare area and then over the vegetated area. The differences in borders between the two scenarios resulted in huge differences in the size of areas associated with erosion and deposition.

5. Conclusion

Wind erosion is a critical environmental problem that threatens the human life in the arid (semi) arid regions. Vegetation cover is the key factor for protecting soil surface from erosive wind. In this study, a set of wind tunnel experiments was performed to investigate the effect of vegetation pattern on wind-blown sediment transport. A scale of 1:50 was used to represent *A. halimus* shrubs. The main findings of this research were: (1) vegetation pattern has a significant effect on wind-blown mass transport, due to the effect of the vegetation on wind-flow turbulence; (2) whereas the vegetation pattern of rows parallel to the dominant wind direction decreases the total mass transport in a region, it may not provide the required protection for areas of consideration; (3) in regions vulnerable to wind erosion, the effect of neighboring land units includes the effect on wind speed and the regulation of sediment flowing from one land unit to the neighboring land units. The current study has provided some insights on the behavior of wind-blown sediment transport in both vegetated, bare land units and at the border between these units. But the results of the current paper are limited to simulated vegetation, to the size of sediment used and to the applied wind speed. And therefore, for deeper understanding of the effects of vegetation cover and patterns on wind-blown sediment transportation, we think further simulations should be conducted using:

- sediment from the regions where the simulated vegetation grows,
- different ranges of wind speed,
- additional variations of vegetation patterns as found in the areas where the vegetation grows.

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References

- Abdourhamane Toure, A., Rajot, J.L., Garba, Z., Marticorena, B., Petit, C., Sebag, D., 2011. Impact of very low crop residues cover on wind erosion in the Sahel. *Catena* 85 (3), 205–214.
- Bowker, G.E., Gillette, D.A., Bergametti, G., Marticorena, B., 2006. Modeling flow patterns in a small vegetated area in the northern Chihuahuan Desert using QUIC (Quick Urban & Industrial Complex). *Environmental Fluid Mechanics* 6 (4), 359–384.
- Bowker, G.E., Gillette, D.A., Bergametti, G., Marticorena, B., Heist, D.K., 2007. Sand flux simulations at a small scale over a heterogeneous mesquite area of the northern Chihuahuan Desert. *Journal of Applied Meteorology and Climatology* 46 (9), 1410–1422.

- Bowker, G.E., Gillette, D.A., Bergametti, G., Marticorena, B., Heist, D.K., 2008. Fine-scale simulations of aeolian sediment dispersion in a small area in the northern Chihuahuan Desert. *Journal of Geophysical Research, F: Earth Surface* 113 (2).
- Burri, K., Gromke, C., Lehning, M., Graf, F., 2011. Aeolian sediment transport over vegetation canopies: a wind tunnel study with live plants. *Aeolian Research*. doi:10.1016/j.aeolia.
- Chandler, D.G., Saxton, K.E., Busacca, A.J., 2005. Predicting wind erodibility of loessial soils in the Pacific Northwest by particle sizing. *Arid Land Research and Management* 19 (1), 13–27.
- Chang, E.H., Chen, C.T., Chen, T.H., Chiu, C.Y., 2011. Soil microbial communities and activities in sand dunes of subtropical coastal forests. *Applied Soil Ecology* 49 (1), 256–262.
- Chappell, A., Warren, A., 2003. Spatial scales of ¹³⁷Cs-derived soil flux by wind in a 25 km² arable area of eastern England. *Catena* 52 (3–4), 209–234.
- Chen, J., Franklin, J.F., Spies, T.A., 1995. Growing-season microclimatic gradients from clearcut edges into old-growth Douglas-fir forests. *Ecological Applications* 5 (1), 74–86.
- Cornelis, W.M., 2006. Hydroclimatology of wind erosion in arid environments (Chapter 9). In: D'Odorico, P., Porporato, A. (Eds.), *Dryland Ecohydrology*. Springer, Dordrecht, The Netherlands, pp. 141–157.
- Cornelis, W.M., Gabriels, D., 2004. A simple model for the prediction of the deflation threshold shear velocity of dry loose particles. *Sedimentology* 51 (1), 39–51.
- Cornelis, W.M., Gabriels, D., 2005. Optimal windbreak design for wind-erosion control. *Journal of Arid Environments* 61 (2), 315–332.
- Dierickx, W., Gabriels, D., Cornelis, W., 2001. A wind tunnel study on wind speed reduction of technical textiles used as windscreen. *Geotextiles and Geomembranes* 19 (1), 59–73.
- Drenova, A.N., 2011. Ancient continental dunes in the upper volga basin: their orientation, structure, granulometric composition. *Geomorfologiya* 1, 37–48.
- Floyd, K.W., Gill, T.E., 2011. The association of land cover with aeolian sediment production at Jornada Basin, New Mexico, USA. *Aeolian Research* 3 (1), 55–66.
- Fryrear, D.W., Saleh, A., Bilbro, J., Schomberg, H., Stout, J., Zobeck, T., 1998. Revised Wind Erosion Equation (RWEQ). Wind Erosion and Water Conservation Research Unit, Technical Bulletin 1. Southern Plains Area Cropping Systems Research Laboratory, USDA-ARS.
- Gabriels, D., Cornelis, W., Pollet, I., Van Coillie, T., Ouessar, M., 1997. The I.C.E. wind tunnel for wind and water erosion studies. *Soil Technology* 10 (1), 1–8.
- Gash, J.H.C., 1986. Observations of turbulence downwind of a forest–heath interface. *Boundary-Layer Meteorology* 36 (3), 227–237.
- Hassine, A.B., Lutts, S., 2010. Differential responses of saltbush *Atriplex halimus* L. exposed to salinity and water stress in relation to senescing hormones abscisic acid and ethylene. *Journal of Plant Physiology* 167 (17), 1448–1456.
- Heisler, G.M., Dewalle, D.R., 1988. 2. Effects of windbreak structure on wind flow. *Agriculture, Ecosystems and Environment* 22–23(C), 41–69.
- Hesse, P.P., Magee, J.W., van der Kaars, S., 2004. Late Quaternary climates of the Australian arid zone: a review. *Quaternary International* 87–102.
- Hupy, J.P., 2004. Influence of vegetation cover and crust type on wind-blown sediment in a semi-arid climate. *Journal of Arid Environments* 58 (2), 167–179.
- Irvine, M.R., Gardiner, B.A., Hill, M.K., 1997. The evolution of turbulence across a forest edge. *Boundary-Layer Meteorology* 84 (3), 467–496.
- Jensen, J., 1958. The model-law for phenomena in natural wind. *Ingeniøren* 2, 121–128.
- King, J., Nickling, W.G., Gillies, J.A., 2005. Representation of vegetation and other nonerodible elements in aeolian shear stress partitioning models for predicting transport threshold. *Journal of Geophysical Research, F: Earth Surface* 110 (4).
- Lancaster, N., Baas, A., 1998. Influence of vegetation cover on sand transport by wind: field studies at Owens Lake, California. *Earth Surface Processes and Landforms* 23 (1), 69–82.
- Leenders, J.K., 2006. Wind erosion control with scattered vegetation in the Sahelian zone of Burkina Faso. Doctoral thesis Wageningen Agricultural University, Wageningen.
- Leenders, J.K., van Boxel, J.H., Sterk, G., 2007. The effect of single vegetation elements on wind speed and sediment transport in the Sahelian zone of Burkina Faso. *Earth Surface Processes and Landforms* 32 (10), 1454–1474.
- Leenders, J.K., Sterk, G., Van Boxel, J.H., 2011. Modelling wind-blown sediment transport around single vegetation elements. *Earth Surface Processes and Landforms* 36 (9), 1218–1229.
- Li, Z., Wu, S., Dale, J., Ge, L., He, M., Wang, X., Jin, J., Liu, J., Li, W., Ma, R., 2008. Wind tunnel experiments of air flow patterns over nabkhas modeled after those from the Hotan River basin, Xinjiang, China (II): vegetated. *Frontiers of Earth Science in China* 2 (3), 340–345.
- Lopez, M.V., Sabre, M., Gracia, R., Arrue, J.L., Gomes, L., 1998. Tillage effects on soil surface conditions and dust emission by wind erosion in semiarid Aragon (NE Spain). *Soil and Tillage Research* 45 (1–2), 91–105.
- Martínez-Fernández, D., Walker, D.J., 2011. The effects of soil amendments on the growth of *Atriplex halimus* and *Bituminaria bituminosa* in heavy metal-contaminated soils. *Water, Air, and Soil Pollution*. doi:10.1007/s11270-011-0839-01-10.
- Maurer, T., Herrmann, L., Stahr, K., 2009. The effect of surface variability factors on wind-erosion susceptibility: a field study in SW Niger. *Journal of Plant Nutrition and Soil Science* 172 (6), 798–807.
- Michels, K., Sivakumar, M.V., Allison, B.E., 1995. Wind erosion control using crop residue. II. Effects on millet establishment and yields. *Field Crops Research* 40 (2), 111–118.
- Molina-Aiz, F.D., Valera, D.L., Álvarez, A.J., Madueño, A., 2006. A wind tunnel study of airflow through horticultural crops: determination of the drag coefficient. *Biosystems Engineering* 93 (4), 447–457.
- Munson, S.M., Belnap, J., Okin, G.S., 2011. Responses of wind erosion to climate-induced vegetation changes on the Colorado Plateau. *Proceedings of the National Academy of Sciences of the United States of America* 108 (10), 3854–3859.
- Musick, H.B., Trujillo, S.M., Truman, C.R., 1996. Wind-tunnel modelling of the influence of vegetation structure on saltation threshold. *Earth Surface Processes and Landforms* 21 (7), 589–605.
- Nanney, R.D., Fryrear, D.W., Zobeck, T.M., 1993. Wind erosion prediction and control. *Water Science and Technology* 28 (3–5), 519–527.
- Raupach, M.R., 1990. Turbulent transfer in plant canopies. *Plant Canopies*, pp. 41–61.
- Raupach, M.R., 1992. Drag and drag partition on rough surfaces. *Boundary-Layer Meteorology* 60 (4), 375–395.
- Raupach, M.R., Gillette, D.A., Leys, J.F., 1993. The effect of roughness elements on wind erosion threshold. *Journal of Geophysical Research* 98 (D2), 3023–3029.
- Ruiz-Mirazo, J., Robles, A.B., 2011. Short- and medium-term response of *Atriplex halimus* L. to repeated seasonal grazing in south-eastern Spain. *Journal of Arid Environments* 75 (6), 586–595.
- Skidmore, E.L., Hagen, L.J., 1977. Reducing wind erosion with barriers. *Transactions of the American Society of Agricultural Engineers* 20 (5), 911–915.
- Sterk, G., Jacobs, A.F.G., Van Boxel, J.H., 1998. The effect of turbulent flow structures on saltation sand transport in the atmospheric boundary layer. *Earth Surface Processes and Landforms* 23 (10), 877–887.
- Stroosnijder, L., 2007. Rainfall and land degradation. In: Sivakumar, M.V.K., Ndiang'ui, N. (Eds.), *Climate and Land Degradation*. Springer, Berlin, pp. 167–195.
- Thomas, R.J., Turkelboom, F., 2008. An integrated livelihoods-based approach to combat desertification in marginal drylands. In: Lee, C., Schaaf, T. (Eds.), *Future of Drylands*. Springer, Dordrecht, pp. 631–646.
- Todd, R.W., Guo, W., Stewart, B.A., Robinson, C., 2004. Vegetation, phosphorus, and dust gradients downwind from a cattle feedyard. *Journal of Range Management* 57 (3), 291–299.
- Udo, K., Takewaka, S., 2007. Experimental study of blown sand in a vegetated area. *Journal of Coastal Research* 23 (5), 1175–1182.
- Udo, K., Kuriyama, Y., Jackson, D.W.T., 2008. Observations of wind-blown sand under various meteorological conditions at a beach. *Journal of Geophysical Research, F: Earth Surface* 113 (4).
- Van De Ven, T.A.M., Fryrear, D.W., Spaan, W.P., 1989. Vegetation characteristics and soil loss by wind. *Journal of Soil and Water Conservation* 44 (4), 347–349.
- Wang, S., Zhao, X., Qu, H., Zuo, X., Lian, J., Tang, X., Powers, R., 2011. Effects of shrub litter addition on dune soil microbial community in horqin sandy land, Northern China. *Arid Land Research and Management* 25 (3), 203–216.
- White, B.R., 1996. Laboratory simulation of aeolian sand transport and physical modeling of flow around dunes. *Annals of Arid Zone* 35 (3), 187–213.
- Wuyts, K., Verheyen, K., De Schrijver, A., Cornelis, W.M., Gabriels, D., 2008. The impact of forest edge structure on longitudinal patterns of deposition, wind speed, and turbulence. *Atmospheric Environment* 42 (37), 8651–8660.
- Youssef, F., Visser, S., Karssenbergh, D., Bruggeman, A., Erpul, G., 2012. Calibration of RWEQ in a patchy landscape: a first step towards a regional scale wind erosion model. *Aeolian Research* 3 (4), 467–476.
- Zhao, F., Liu, H., Yin, Y., Hu, G., Wu, X., 2011. Vegetation succession prevents dry lake beds from becoming dust sources in the semi-arid steppe region of China. *Earth Surface Processes and Landforms* 36 (7), 864–871.
- Zou, X.Y., Cheng, H., Zhang, C.L., Zhao, Y.Z., 2007. Effects of the Magnus and Saffman forces on the saltation trajectories of sand grain. *Geomorphology* 90 (1–2), 11–22.