The effect of vegetation patterns on Aeolian mass flux at regional scale: A wind tunnel study

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ABSTRACT

Although insight on the effect of vegetation pattern on Aeolian mass transport is essential for re-planting degraded land, only limited knowledge on this effect is available. The objective of this research was to understand the effect of vegetation design on the Aeolian mass flux inside a single land unit and at the borders among land units. A simulation of *Atriplex halimus* shrubs inside a wind tunnel was made, and sand redistribution was measured after the application of 200-230 seconds wind at a speed of 11 ms^{-1}. The study showed that: 1) sediment maximum transport inside a single land unit is related to the neighboring land units and to the vegetation pattern within both the unit itself and the neighboring land units; 2) the effect of neighboring land units includes the protection effect and the ruling of sediment crossing from one land unit to the neighboring land units; 3) for the designing of re-planting of degraded land the 'streets' (zones of erosion areas similar to streets) effect need to be considered; and 4) in addition to the general knowledge needed on the effect of vegetation pattern on the erosion and deposition within an area, it is important to have insight on the redistribution of sediment at small scales upon the aim of the project.

Key words: wind erosion; vegetation pattern; wind-blown mass transport; wind tunnel

Introduction

Wind erosion is a significant environmental problem in arid and semi-arid regions of the Earth (Stroosnijder 2007, Cornelis 2006). Suspended dust particles may cause health problems to the inhabitants (Thomas and Turkelboom 2008) and saltating particles may cause crop damage and reduce soil fertility (Nanney et al. 1993). Re-planting of degraded land is a widely accepted method to reduce sediment transportation processes (Leenders 2006, Wang et al. 2011, Zhao et al. 2011). Leenders et al. (2007) showed that the parkland system, in which a combination of trees and shrubs are distributed over the area, enable potential for regional-scale protection against the negative impact of wind erosion.

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 (Abdourhamane Toure et al. 2011, Leenders et al. 2011, Munson et al. 2011, Sterk et al. 1998, Udo and Takewaka 2007, Van De Ven et al. 1989). Also, research on stabilization of moving sand dunes related the reduction of sand movement to the increased trapping capacity of the vegetation cover (Chang et al. 2011, Drenova 2011, Floyd and Gill 2011, Hesse et al. 2004).

Insight on the effectiveness of vegetation in reducing aeolian sediment transport is fundamental for selecting a suitable design for re-vegetate degraded land (Burri et al. 2011, King et al. 2005). However, studies on the effect of vegetation on Aeolian sediment transport in the fields alone are not sufficient. This is because in the fields, the effect of vegetation is not separated from the effect of other factors such as changes in vegetation cover, soil properties, soil surface roughness and crust (Lopez et al. 1998). Therefore, wind tunnel experiments constitute an additional method to investigate the relationship between vegetation and Aeolian sediment transport (Cornelis and Gabriels 2004, Gabriels et al. 1997). Most of previous wind tunnel experiments on reducing wind-blown mass transport with vegetation have focused on the simulation of field conditions at the plot or point scale (Musick et al. 1996, Li et al. 2008, Udo and Takewaka 2007). The results of these studies improved our knowledge on the effect of vegetation on Aeolian mass transport at small scales. However, they are insufficient for understanding wind erosion at a regional scale. This is because in wind erosion regions, land use in one land unit may affect wind erosion processes in neighboring land units (Hupy 2004, Leenders 2006). Therefore, to have insight on the effect of vegetation at the regional scale, it is important to retrieve data representing processes taking place along a land unit and at transitions between land units. The objective of this study is to provide deeper understanding of the effect of vegetation cover and patterns on the change in aeolian mass flux by wind tunnel experiments. The research questions are: 1) What is the change in aeolian sediment transport at borders between land units? 2) What is the effect of vegetation pattern on the distribution of aeolian mass transport across fields? 3) What is the role of vegetation pattern on total area associated with erosion or deposition along a land unit?

Methods

Wind tunnel: This research was conducted in the wind tunnel of the International Center for Eremology (ICE), Ghent University, Belgium (Cornelis and Gabriels 2004, Gabriels et al. 1997). Wind speed was measured with vane probe-type anemometers (Gabriels et al. 1997) placed at X (length) = 5.85 m (measured from the entrance), Y (width) = 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, 0.5 m wide and 0.01m deep tray. To create a roughness similar to the sand, sandpaper was fixed 1.5 m before the tray and on the area at its left and right side (Fig. 1).

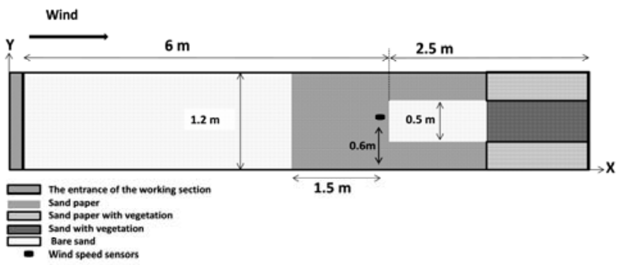

Figure 1. Setup of the wind tunnel experiments at the ICE, Ghent Belgium.

The wind velocity during each run was 11 m s^{-1} at a height of 1.10 m above the (solid) sand paper and at a distance of 6 m from the test section entrance, corresponding to a shear velocity of 0.26 m s^{-1} determined following the procedure of Cornelis and Gabriels (2004).

In these experiments a vegetation model that is similar to *Atriplex halimus* shrubs was used, applying a downscaling ratio of 1:50. This scale gives the option to simulate the height of *Atriplex halimus* and the distance among the shrubs in real fields under boundary layer of the wind tunnel. The modeled shrubs were between 2 and 2.5 cm high, representing 1 and 1.25 m-high *Atriplex halimus* shrubs in the field. The rate of the surface covered by the vegetation was 10 - 11% throughout the experiment.

Wind-driven sediment transport was measured for the simulation of five vegetation patterns that are shown in figure 2 and are explained below:

(I) P.A: 36 individual modeled shrubs were positioned on a regular grid; (II) P.B: 32 individual modeled shrubs were placed in a sequence of offsetting the second, fourth, sixth and eighth rows of shrubs in the Y direction; (II) 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; (IV) 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; (V) PE: movement of sediment from vegetated to bare land was tested using 36 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 was the same for all patterns (Fig. 2).

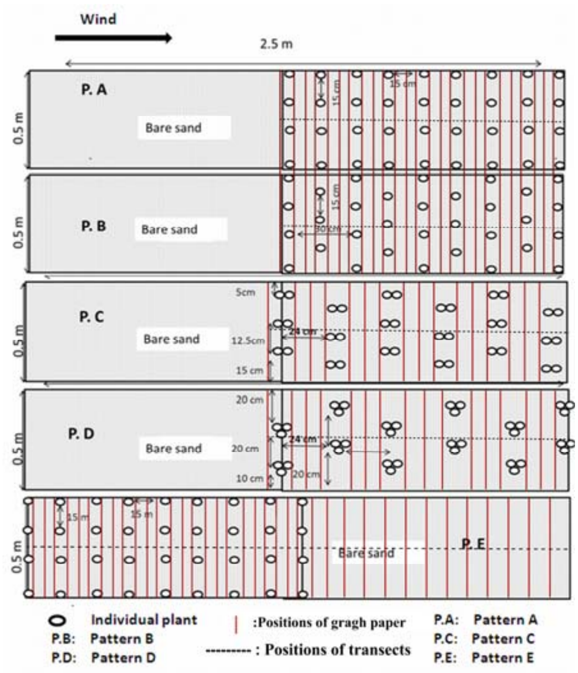

Figure 2.Tested vegetation patterns in the wind tunnel experiment.

A 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. The chosen wind speed provides transport of sand and did not affect the shape of the modeled vegetation in the wind tunnel. Each test lasted 200-230 seconds (except run 3 in P.D pattern) and generally, after this period, all sand in the bare (upwind) part of the tray was eroded in patterns P.A, P.B, P.C and P.D. A graph paper (with a plaster) of 0.5 x 0.25 m and around 0.0003 m thickness was used to measure the sand height along the experimental tray. The paper was inserted carefully in the pre-wetted sand perpendicular to the wind direction and the sand topography was drawn on the paper. Pre-wetting the sand after each run prevented the surface to collapse when inserting the graph paper. Then, the heights of the sand were read directly from the paper with a 1 cm horizontal interval, therefore, at each position of the paper in the tray 51 heights were recorded. Fig. 2 shows the positions at which the sand heights were measured relative to the position of vegetation elements. Geostatistical interpolation of the data was performed using a spherical variogram model (that fitted best the data); maps showing the spatial variation of sand heights along the tray were created by ordinary point kriging (Chappell and Warren 2003).

Results

*Spatial distribution along the experimental tray:*As run 1 can be considered as a preparation run, the spatial distribution of sand height along the tray was similar for runs 2 and 3 for patterns P.A, P.B, P.C and P.D. Fig. 3 shows the spatial distribution of the averaged sand height. As the sand height along the tray was 1 cm before the test, in Fig. 3, values above 1 cm represent deposition and values below 1 cm represent erosion. The first 125 cm of the sand tray is not included for patterns P.A, P.B, P.C and P.D, because this part of the tray was empty after the wind application. In pattern P.A, deposition happened behind shrubs.

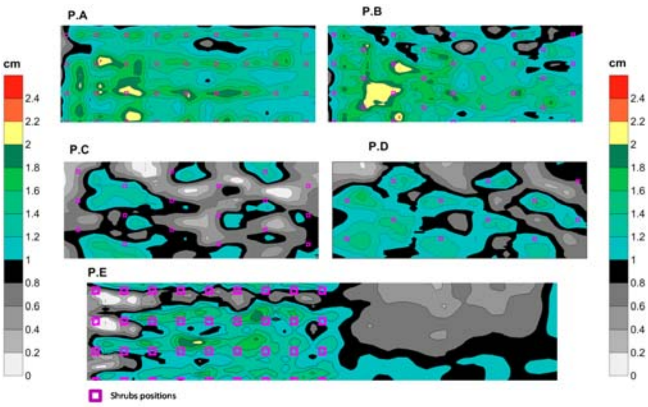

Figure 3 Spatial distribution of sediment height over the tray for 2 runs average of each vegetation pattern.

The amount of deposition reduced from the upwind border to the downwind border of the vegetated unit. In the zones between rows parallel to the wind direction, erosion gradually increased towards the downwind border. These results are in line with the findings in field research by Bowker et al. (2008), who reported 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 measured in the upwind half of the tray. After the fifth row of shrubs (perpendicular to wind direction) up to the end of the tray, a decreased deposition and some erosion was recorded. With patterns P.C and P.D, erosion was prevailing, though little levels of deposition were measured behind the shrubs. The third run of 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. At the bare part of the plot, erosion started at a distance of 5-10 cm, which is equal to almost 2-5 times the height of the vegetation elements.

Average sediment height for the tested area: To regain the general style in erosion or deposition in the direction of the wind, transects parallel to the wind direction were calculated. For every 5 cm the average of all sand heights was calculated and plotted (Fig 4). As in Fig. 3, the first 125 cm are not included for pattern P.A, P.B, P.C and P.D, as this part of the tray was almost empty after the wind application. Fig. 4 shows that run 2 and run 3 for patterns P.A, P.B, P.C and P.D have comparable results, enabling observation of clear, consistent variation between the patterns. The minor differences can be attributed to the small variability of the wind speed among the runs. Patterns P.A and P.B show a small zone of erosion at the border between the bare and vegetated parts of the tray. As the shear velocity of the wind is reduced (due to vegetation presence), mass transport degree reduces as well. Net deposition occurred 2.5 to 120 cm downwind from the vegetation edge. The firstly high and downwind-decreasing deposition indicates a decrease in the sediment concentration due to the decrease in the sand supply as a large part of sand became trapped by the upwind shrubs. Deposition reaches the highest level at 20 cm downwind from the border. Beyond this, deposition decreases gradually and becomes almost at equilibrium (neither erosion nor deposition) at the distance of around 100 cm from the border. In contrast with patterns P.A and P.B, pattern P.C, net erosion continues within the downwind distance from the edge of the vegetation zone. The more sparsely distributed shrubs seemingly associated with less frictional resistance, and hence shear velocity was perhaps higher, resulting in higher erosion rates. The continued erosion in pattern P.C along the first 10-20 cm from the vegetation edge indicates that the vegetation elements were too sparse to protect the area from erosion, although the surface cover was similar as in pattern P.A and P.B.

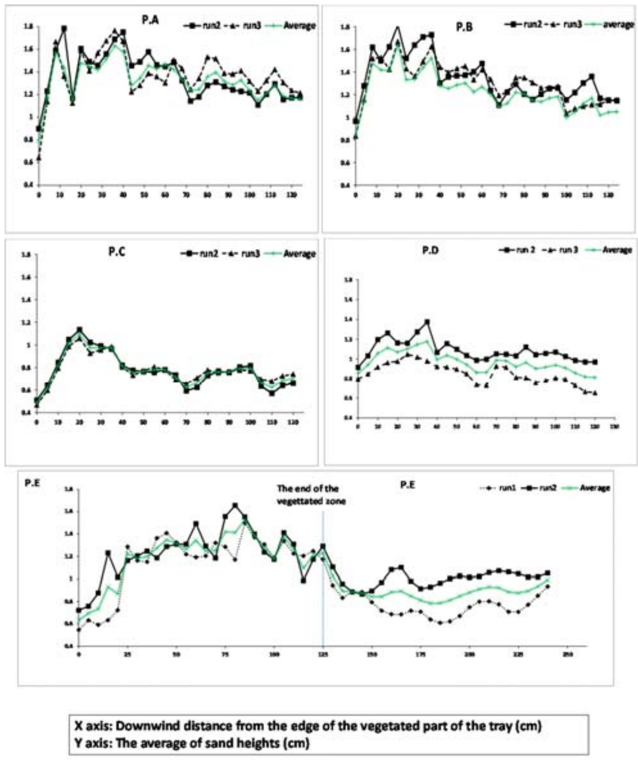

Figure 4. Average of sand heights along the downwind distance for run 2 and 3 of each vegetation pattern.

with pattern P.D, sand heights show erosion in the first 10 cm after the border, after which deposition occurs in run 2 and a decreased 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, and no significant erosion or deposition was observed up to the end. The results of run 3 show again a slight increase in erosion from 35 cm up to 65 cm, and after which a decrease in erosion is observed between 65 cm and 85 cm. From a distance of 85 cm the erosion increased up to the end of the tray. In the pattern P.E (-vegetation to bare- scenario), net deposition only starts from a distance of 10-20 cm from the border of the vegetated field. As observed in P.A, whith a similar vegetated pattern, the shrubs resulted in reduced shear velocity, and hence decreased erosion compared to a bare field. However, erosion was not partially compensated for by deposition, as it was the case in P.A. This is because a sediment source upwind of the vegetated unit was absent in P.E.

Discussion

Large-scale consideration: The effect of borders between different land units on the aeolian mass flux is vital for understanding wind erosion at the regional scale. The differences of aeolian mass flux within vegetated and bare field along the prevailing wind direction detected a main concept linked to the border effect:

Sediment transport within bare and vegetated land units. Fryrear et al. (1998) reported that, when sediment transport along a bare land unit, it is expected that the absolute maximum transport is reached after a certain distance when the field length is unlimited. When sediment passes a border with vegetation, the theory expects deposition to occurr until the starting of a new transport process. The patterns P.A and P.B and run 2 for pattern P.D show results in the line with the theory. A sediment-laden air flow reaches the border of vegetation, after which deposition happens and at the end equilibrium is established. Although for patterns P.A. and P.B equilibrium was not yet reached, the trend clearly shows a decreasing deposition. This result agrees also 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 increases inside the vegetated area from the upwind borders.Results obtained with pattern P.C and run 3 of P.D disagree with the theory. With the P.C pattern, sediment transport within the vegetated area is higher than within the bare area. Several previous studies indicated that a limited surface cover (5 - 7.5 %) under a certain minimum wind speed could cause increase in the Aeolian mass fluxes (Maurer et al. 2009, Michels et al. 1995, Raupach 1990, Raupach 1992, Raupach et al. 1993, Sterk et al. 1998). However, these studies did not mention the effect of the cover pattern . The effect of the wind speed on the increased mass flux is illustrated in the difference between run 2 and 3 for pattern P.D. In run 2 the pattern and the cover was sufficient to reach an equilibrium between erosion and deposition, whereas in run 3 more erosion occurred. Though the same cover (11%) was used 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. Thus, these different results lead to the conclusion that the vegetation pattern is another factor that may cause increase in the Aeolian mass flux, most probably due to an increase in turbulence.

Small-scale consideration: Beside the investigation of the effect of vegetation pattern on general amount of erosion or deposition in a region, it is important to investigate the effect of vegetation pattern at small scales. In this study, none of the vegetation patterns sufficiently protected the sediment surface to completely stop aeolian mass transport. The small-scale effects of vegetation found in this study are:

A)'Street' effect: This effect refers to the formation of areas of erosion similar to streets. This effect was evident in the P.A pattern having rows of vegetation parallel to the wind direction. In their research, Bowker et al. (2008) showed similar 'streets' of erosion in the downwind direction between shrubs for several dust storms in the north Chihuahuan desert. This effect should be considered while designing re-vegetation projects. Thus, if the goal of the project is to stop sediment from reaching a certain location, pattern P.B might be a more effective pattern than P.A. However, if the aim is to decrease sediment movement within the entire region, pattern P.A can be the best. Therefore, with the consideration of prevailing wind direction, the vegetation pattern of rows (shrubs or trees) may result in erosion zones similar to the shape of streets. This allows the movement of a part of the sediment to reach the protected area, but the total sediment movement is reduced.

B) *The spatial sequence of erosion and deposition*. Though in general, patterns P.C and P.D are associated with erosion, a spatial sequence of erosion (at large distance) and deposition (at short distance) was observed. The deposition can be related to the redistribution of the sand on both sides of vegetation 'elements' in the Y direction. This small-scale deposition is not clear and can be neglected when considering the regional scale. However, when the focus of the protection project is taking into account the effect of wind-blown mass flux at the micro-scale, these areas of erosion and deposition may carry specific importance.

C) *Sheltering zone*. The small zone of sheltering of one land unit on a neighboring land unit is similar to the sheltering effect of wind breaks that was determined by several studies to be 10 – 20 times the height of these vegetation (Cornelis and Gabriels 2005, Heisler and Dewalle 1988, Skidmore and Hagen 1977). In this study, it can be shown that the shelter-effect of one land unit on a neighboring land unit is similar to the effect of wind breaks from the size of protection zone. 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 3). 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.3).

Conclusion

A set of wind tunnel experiments were performed to investigate the effect of vegetation pattern on wind-blown sediment transport. A scale of 1:50 was used to represent *Atriplex halimus* shrubs. The main findings of this research were: (1) vegetation pattern affects the wind-blown mass transport, which can be explained by the effect of vegetation on the turbulence of the wind-flow; (2) 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; (3) whereas the vegetation pattern of rows parallel to the dominant wind direction decreases the total mass transport in a region, it does not provide the required protection for areas of consideration. Finally, we think further simulations for sediment transportation with the presence of vegetation cover using sediment from the real wind erosion regions are required. These simulations should be done by the use of different ranges of wind speeds, and by the designing of different vegetation patterns for deeper understanding of the effects of vegetation cover on wind-blown sediment transportation.

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