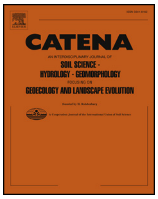
Catena 172 (2019) 421–434

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena



Wind-borne sand mass flux in vegetated surfaces – Wind tunnel experiments with live plants

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ARTICLE INFO

Keywords:
Aeolian sand flux
Vegetated surface
Wind tunnel
Cosmos bipinnatus
Ligustrum lucidum Ait

ABSTRACT

To develop our knowledge of the impact of different vegetation types on aeolian sand flux, a series of experiments conducted in a wind tunnel monitored sand mass flux over a bare surface and in relation to the planted surface of two types of live plants, *Cosmos bipinnatus* and *Ligustrum lucidum Ait*, at different plant densities. Normalized sediment flux decreased with increasing height over a bare surface. However, plants affected the sediment transport system by modifying the vertical distribution of sediment flux within and above the vegetated surface. Sand flux reduced from low to high plant density below the plant height but this pattern reversed above the vegetated surface. Observations of the horizontal profiles of sand flux indicated sediment was transported within the vegetated areas of both plant types in all densities. In low density, the horizontal trend of sand flux was similar to the bare sand surface. In medium density, the sand flux increased slightly within the vegetated surface and decreased beyond the vegetated surface for both plant types. In high density, sediment flux increased from the upwind edge to the middle of the vegetation barrier, and reduced at the downwind end and beyond the vegetated surface of both plant types. Observations of sand flux in different plant densities revealed the influence of plant drag versus the turbulence produced by plants. At a certain distance within the vegetated area, plant drag reduced the sand flux. Although varying between the two plant types, sand flux decreased overall from unplanted to planted configurations.

1. Introduction

Aeolian erosion is a major problem in arid and semi-arid regions of the world and is closely linked with climate and vegetation change (Wu, 1987). In these regions, the production, transport and deposition of sediment by wind are influenced by changes in surface characteristics (N'Tchayi et al., 1994). Dust storms are a serious environmental hazard and are linked to severe wind erosion (Dong et al., 2002). This hazard causes environmental, social and economic problems, impacting adversely on human health as well as increasing pollution, crop damage and sand deposition in wells and streams (Larney et al., 1999; Dong et al., 2002; Prospero et al., 2002; Miri et al., 2009; Sharifikia, 2013). Therefore, studying and finding the most efficient approaches to control wind erosion is essential.

Vegetation is the most efficient protector of the ground surface in controlling aeolian erosion (Wolfe and Nickling, 1993). Vegetation increases surface roughness and extracts momentum from airflow (Musick and Gillette, 1990; Dong et al., 2001). Compared to rigid elements (pebbles, cobbles and boulders), plants extract more momentum due to their flexibility and porosity, thus they are more effective in controlling sediment detachment and transport than rigid elements (Gillies et al., 2002; Hagen and Casada, 2013). Consequently, understanding the effect of plants in reducing blown sediment is important for the re-vegetation of erodible lands for the purpose of wind erosion control (King et al., 2006; Burri et al., 2011; Youssef et al., 2012).

Many studies have been done both in wind tunnels and in the field on the impact of vegetation, and the results indicated that vegetation is the most effective roughness agent for controlling aeolian erosion by sheltering the surface, decreasing wind velocity and trapping soil particles (Okin and Gillette, 2001; Visser et al., 2005; Udo and Takewaka, 2007; Breshears et al., 2009; Bergametti and Gillette, 2010; Humberto and Rattan, 2010; Burri et al., 2011; Leenders et al., 2011; Davidson-Arnott et al., 2012; Walter et al., 2012a; Walter et al., 2012b; Hagen and Casada, 2013; Suter-Burri et al., 2013; Leenders et al., 1994). These studies have focused on the overall protective function of the vegetation

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https://doi.org/10.1016/j.catena.2018.09.006
Received 12 December 2017; Received in revised form 25 July 2018; Accepted 4 September 2018

against wind erosion. Although there have been many important advances in understanding the effect of plants in reducing wind velocity and sand transport (e.g., Wolfe and Nickling, 1993; Breshears et al., 2009; Bergametti and Gillette, 2010; Burri et al., 2011; Leenders et al., 1994), our understanding of airflow processes, vegetation characteristics, and aeolian sediment fluxes is incomplete. Analysing the interaction of wind and plants at various scales is essential for assessment of the local turbulence environment and the wind forces acting on vegetation (Finnigan and Brunet, 1995; Raupach et al., 1996; Dupont and Brunet, 2008).

The effect of roughness elements on airflow and sediment flux has been simulated by solid objects (Musick et al., 1996; Jia et al., 1998; Lee et al., 2002; Minvielle et al., 2003; Poggi et al., 2004; Udo and Takewaka, 2007; Sutton and McKenna-Neuman, 2008), but the results from such studies may not represent entirely the effectiveness of live plants in controlling wind-borne sediment transport in natural environments. This is due to the different effects of plants on airflow and blown sediment in comparison with solid roughness elements. Only limited experimental work has been done in wind tunnels to investigate the reaction of living vegetation to airflow and sediment transport (Burri et al., 2011; Walter et al., 2012a; Walter et al., 2012b; Hagen and Casada, 2013; Suter-Burri et al., 2013).

In order to achieve greater understanding of the effects of vegetation cover and vegetation patterns on wind-transported sediment, further investigations are required to develop efficient re-vegetation strategies for soils vulnerable to erosion, to improve the predictive capabilities of aeolian models and to develop our knowledge of the effectiveness of different vegetation in reducing wind erosion (King et al., 2005).

A series of wind tunnel experiments was conducted in this study to quantify the impact of two types of live plants on sand flux. Although the use of live vegetation is not novel (Kim et al., 2000; Burri et al., 2011; Hagen and Casada, 2013; Suter-Burri et al., 2013), this is the first study in which two different types of live plants are used in a wind tunnel under the same controlled conditions to monitor the sand flux profiles in different vegetation densities. The objective of this study was to investigate the impact of live plants on blown sand flux in different plant densities under various wind velocities.

2. Materials and methods

The experiments were carried out in a 'blowing-type' wind tunnel of the Key Laboratory of Environmental Dynamics on the Loess Plateau, at the Shanxxi Normal University in Xi'an, China (Fig. 1 shows wind tunnel schematically). The length of the tunnel is 15 m with a working section of dimensions of 50 cm wide, 60 cm high and 700 cm long, in which the flow speed can be controlled from 0.1 to 30 m s^{-1}.

Cosmos bipinnatus and *Ligustrum lucidum Ait* (Fig. 1) were used for the experiments. The plants present different morphologies (one a narrow-leafed plant and the other a broad-leafed plant), and both have low flexibility and sufficient resistance to wind and sediment bombardment for use in a wind tunnel.

The plants with a height of about 15 cm were distributed in regular staggered rows in low density, medium density and high density following the same overall planting design patterns. It has been noted that the first third of a wind tunnel length should not be used for measurement (Zingg and Chepil, 1950). Kim et al. (2000) did not install roughness elements (*Distichlis spicata* stalks) in the first five metres of the flow-development sections and they placed the vegetation (with a canopy height of 14.2 cm) in the last flow-development section where the boundary layer was about 15–20 cm in a wind speed of 7 m s^{-1}for a bare surface. Prior to experiments in the present study, wind profiles were measured as a function of distance along the tunnel without plants to select the appropriate location where a boundary layer is well developed to set up vegetation, sand samplers and Pitot tubes.

Burri et al. (2011), Suter-Burri et al. (2013) and Walter et al. (2017) conducted their experiments in vegetation canopies covering eight metres, the length of the test section of the wind tunnel. Abulaiti et al. (2017) installed a simulated vegetation configuration of seven metres length and Gonzales et al. (2017) installed roughness elements throughout the test section of a wind tunnel. The length of vegetation canopy was five metres in Kim et al. (2000)'s study. In the current study, sand flux and wind velocity profiles were monitored upwind, within and downwind of vegetated surfaces, and with the planted surface beginning at a distance of 350 cm downwind of the entrance of the work section where the boundary layer is about 25–30 cm in a wind speed of 8 m s^{-1} for the bare surface case. The planted surface extended to a distance of 550 cm downwind of the entrance of the work section, giving vegetation a fetch of two metres to assess the effect of these specific plant types. The planted surfaces were positioned from 350 cm downwind of the leading edge of the test section of the wind tunnel, which is 15 times the boundary layer thickness ($x = 15\delta$). This meets the general rules of matching mean velocity profiles (10–25 boundary layer height) and is a minimum length entrance required for the velocity defected layer to resemble the boundary-layer profile and for saltation processes to achieve equilibrium (White, 1996).

Funk and Engel (2015) installed a series of across-tunnel sediment traps to measure the variability of sediment transport across the tunnel width. Owing to the side-wall effect of the wind tunnel on airflow and sand flux (Ling, 1994; Dong et al., 2004; Feng et al., 2009; Hong et al., 2018), a series of Pitot tubes and sand samplers were placed in the central line of the tunnel consistent with previous studies to monitor vertical and horizontal profiles of wind velocity and sand flux over planted surfaces and an unplanted surface (Kim et al., 2000; Ni et al., 2003; Liu et al., 2006; Burri et al., 2011; Hagen and Casada, 2013; Walter et al., 2017; Gonzales et al., 2017; Hong et al., 2018). Sand flux measurements were not taken across the tunnel due to unavailability of additional sediment samplers.

Mean wind velocities were measured at each position at twenty heights commencing with 3 cm above the test-section floor to 44 cm, under free-stream wind velocities of $U_\delta = 6$, 8, 12 and 14 m s^{-1} (Table 1 and Fig. 2).

Sediment mass flux measurements were taken using four segmented sand samplers (WITSEG samplers) constructed according to Dong et al. (2004). Each sampler is sectioned into fifteen chambers of 2 × 1 cm openings to collect the blown sediments up to 30 cm height. The samplers were set into the sand so that the bottom of the lowest opening of the sampler was flush with the sand surface. Four locations were included to measure vertical and horizontal sand flux along the wind tunnel. The location of sand samplers is summarized in Table 2 and shown in Fig. 3. Sand flux sampling was done in bare sand configuration and in configurations with *C. bipinnatus* and *L. lucidum* in high, medium and low densities (Fig. 3). Wind velocities of 12 and 15.5 m s^{-1} were applied to measure sand flux in all configurations. These wind speeds were chosen to ensure that enough sand particles were detached from the bare surface (Dong et al., 2004; Delgado-Fernandez, 2010; Kheirabadi et al., 2018) and transported within each vegetation configuration for these specific experiments and plant types, with the aim of comparing the results in different configurations (unplanted and planted surfaces) and between the two plant types (Burri et al., 2011; Suter-Burri et al., 2013; Gonzales et al., 2017). Duration of 270 s for a wind speed of 12 m s^{-1} and 300 s for a wind speed of 15 m s^{-1} were applied to yield a sufficient amount of sediment in the samplers without overloading and to reduce plant damage from sand bombardment.

About 84% of sand particles size lay within the 100–250 μm range, which falls within the sand range for saltation (Pye and Tsoar, 1990) and corresponds to high vulnerability of sand particles to aeolian erosion (Chandler et al., 2004). The mean diameter ($-\log_2 d$) of the sand particles was 0.18 mm (2.42ϕ), and the sands are well sorted (standard deviation 0.41, skewness 0.05, and kurtosis 1.02). The measured threshold wind velocity of the sand was 5 m s^{-1}.