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Airflow and sediment movement within an inland blowout in Hulun Buir sandy grassland, Inner Mongolia, China

Yu Sun [a], Eerdun Hasi [a,*], Meiping Liu [a], Huishi Du [b], Chao Guan [a], Binbin Tao [a]

[a] College of Resources Science and Technology, Beijing Normal University, Beijing 100875, China
[b] Institute of Ecological Environment, Jilin Normal University, Siping 136000, China

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ABSTRACT

We measured wind flows and sediment transport rates through a blowout in Hulun Buir grassland, Inner Mongolia. Topography and the angle of incidence between the approaching wind and the blowout long-axis significantly affected the air flow. Flow separated and decelerated at the western wall and accelerated towards the east, until maximum wind speed occurred at the top of the depositional lobe, and then decelerated on the lee side. When airflow emerged on the eastern wall, resultant directions were always NW. When winds approached from directions within 17.5° of the blowout axis, both the northwestern and southwestern walls developed turbulent flow, and significant topographic steering occurred. The deceleration zone expanded eastwards from 10.3 to 12.8 m from the western rim. When the wind direction was more oblique than 17.5°, turbulent flow at the southwestern wall disappeared. ‘S-shaped’ flow intensified, causing more pronounced steering at the bottom, but topographic steering elsewhere was reduced, and the boundary of the deceleration moved to 10 m from the western rim. Minor sediment deposition occurred on the western wall, while other parts were eroded; maximum sediment transport occurred at the top of the depositional lobe. The approaching wind speed affected the sediment transport rate more than the direction; and spatial variability in sediment transport reflected differences in compaction, vegetation coverage, slope, aspect, and upwind sediment availability, resulting in asymmetrical development. Overall, flow-form interactions governed the flow structures and controlled the evolution of the blowout via sediment transport.

1. Introduction

Blowouts occur in both coastal and inland environments from low to high latitudes (Hesp, 2002; Dominguez and Barbosa, 2004; Hugenholtz and Wolfe, 2006; Wang et al., 2007), they commonly occur as depressions or hollows formed by aeolian erosion (Hesp and Hyde, 1996; Byrne, 1997; Hesp and Pringle, 2001; Hesp, 2002; Hugenholtz and Wolfe, 2006). Blowouts consist of two parts: a deflation basin and a depositional lobe, and they are classified into three categories based on their topographic shape: saucers, bowls, and troughs (Hesp and Walker, 2012; Smyth et al., 2013; Sun et al., 2015). In China, blowouts are mainly distributed in the Hunlun Buir, Otingdag, Horqin and Mu Us sandy lands (Zhu and Wu, 1981; Wu, 1987) and adjacent sandy grasslands (Zhang et al., 2007; Wang and Hasi, 2009; Yan et al., 2009; Li et al., 2013). Blowouts are precursors to dune reactivation, and in arid regions dune field reactivation is typically a form of land degradation and is the primary manifestation of desertification (Zhu, 1989; Barchyn and Hugenholtz, 2013), thus they have attracted significant research attention. To date, many studies have focused on the morphology (Catto et al., 2002), airflow patterns (Pluis and Boxel, 1993; Hesp, 1996; Fraser, 1998; Pease and Gares, 2013; Garès and Pease, 2015), erosional and depositional patterns (Bate and Ferguson, 1996; Hesp and Hyde, 1996; Halls and Bennett, 2012) and evolution (Jungerius, 1984; Gares and Nordstrom, 1995; Abhar et al., 2015) of blowouts, especially those developed in coastal dunes. However, there have been few studies of blowouts developed on inland flat grasslands (Hugenholtz and Wolfe, 2006).

The airflow within the blowout behaves significantly different from that of the approaching wind (Smyth et al., 2013): it is topographically manipulated, which causes significant steering, acceleration and even turbulent flow in some circumstances (Hesp and Pringle, 2001; Hugenholtz and Wolfe, 2009; Hesp and Walker, 2012; Smyth et al., 2012; Jackson et al., 2013; Smyth et al., 2013). These findings confirm the occurrence of form-flow feedback effects (Hugenholtz and Wolfe, 2009), and that they are

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* Corresponding author.
E-mail address: hasi@bnu.edu.cn (E. Hasi).

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essential component of sediment transport and development within the blowout. Measurements of the flow dynamics within coastal trough blowouts (Hesp, 1996; Hesp and Hyde, 1996; Hesp and Pringle, 2001; Hansen et al., 2009) found that the wind flow was accelerated within the throat, resulting in high wind speeds along the deflation basin and erosional walls. This is followed by deceleration in the wider deflation basin and acceleration along the erosional marginal walls and up the windward face of the depositional lobe. However, it is unclear whether or not airflow dynamics within the inland blowouts developed on flat grassland follow a similar pattern, and few studies have examined the effects of topography on airflow direction.

Spatial differences in sand transport influence the patterns of erosion and deposition within blowouts and play an important role in their morphological development. Sediment transport within blowouts has been measured using erosion pins (Jungerius et al., 1981; Jungerius and Meulen, 1989; Jungerius et al., 1991; Pluis, 1992; Byrne, 1997; Hugenholtz and Wolfe, 2009), sand traps (Gares, 1992; Byrne, 1997) and topographic surveys (Gares and Nordstrom, 1988; Käyhkö, 2007). However, only Smyth et al. (2014) have measured sediment transport in relation to near surface wind speed within a coastal trough blowout; they found that where airflow was steadiest, sediment transport rate was greatest. Similar research has not yet been conducted within closed-system inland blowouts, which may respond differently because of their internally-generated sediment supply.

Surface conditions, such as vegetation coverage and soil compaction reflect the ability of the landform to resist erosion, and play an important role in sediment transport. Currently, only a few studies of coastal blowouts have demonstrated that vegetation coverage can influence the evolution of blowouts by controlling the patterns of erosion and deposition (Schwendiman, 1977; Jungerius et al., 1991; Gares and Nordstrom, 1995). However, no attention has been paid to the relationship between sediment transport and soil compaction, either in coastal or inland environments.

The aim of the present study was simultaneously to measure wind speed and direction at different locations within an inland elliptical blowout in order to quantify and better understand the form–flow relationship and its effects on sediment transport and topographic development. It is hoped that the results of the study will also provide an improved understanding of the desertification process, which is manifested by blowouts in inland flat sandy grassland environments.

2. Regional setting

Hulun Buir sandy grassland, in the Inner Mongolian Plateau, China, is an important ecological shelter zone for Northeast Asia; however, it is also ecologically fragile, facing threats from desertification. The sandy grassland has a temperate continental monsoon climate with a mean annual temperature of −1.3 °C and mean annual precipitation of 310 mm, with 70% of the rainfall events concentrated in June, July and August. The average annual evaporation in the area ranges is about 1700 mm, the annual wind speed is 3.8 m s^{-1}, and the prevailing wind direction is NW. The local landscape consists of the alternating distribution of flat grassland and fixed and semi-fixed dune fields with elevations varying between 600 and 800 m. The dune field consists of three zones from north to south (Fig. 1a), covering about 21.5% of the area of the sandy grassland. The zonal soil of the grassland is calciustoll, derived from Quaternary fluviolacustrine sediments, and the dominant soil in the dune field is aeolian sandy soil. The constructive plants of the steppe community in the eastern part of the sandy grassland are *Filifolium sibiricum, Stipa grandis* and *Leymus chinensis* etc. Towards the west, because of the decreased humidity, the dominant species mainly consist of xeromorphic taxa such as *Stipa krylovii*, *Cleistogenes spuarrosa* and *Caragana microphylia Lam*.

The location of the study is the northeastern part of the flat Hulun Buir sandy grassland (Fig. 1a). Within the study area, there are more than 400 blowouts of different sizes, shapes, and stages of development distributed along roads or randomly distributed in grassland (Fig. 1b). The length of the deflation basins ranges from 6 to 200 m and the dominant length (from 20 to 40 m) accounts for 40% of the total. The dominant orientation of the deflation basins, accounting for approximately 30% of the total, is W-E (between 168.75–78.75°and 191.25–101.25°), aligned roughly with the regional resultant sand transport direction. The length–width ratio ranges from 1 to 5.5, and roughly 43% of the blowouts are trough-shaped (length–width ratio greater than 2). Depositional lobes are located on the eastern rim of the deflation basins, parallel to the alignment of the deflation basins.

The study site is located to the northeast of the most northern dune field zone (49°14′ N, 119°37′ E), and is a relatively small elliptical blowout (Fig. 1c), which is evolving from a saucer to a trough shape. The deflation basin is 33.9-m long, 14.9-m wide, 2.0-m deep and has a W-E (275–95°) orientation, aligned with the regional resultant sand transport direction (Fig. 1d). Evidence of collapse can be seen on both the northern and southern walls. The southern wall (from 15 to 25°) is almost vertical and is steeper than the northern wall (from 10 to 20°). The western wall is shorter with a gentler slope (approximately 15°), and the eastern wall is longer and steeper (approximately 25°). The dark area along the rim of the walls is the original soil (from 20 to 30 cm in depth) which is exposed because of the intensive erosion (Fig. 2a). The depositional lobe is situated immediately east of the deflation basin and is 27.1-m long and 26.8-m wide; the crest of the depositional lobe is approximately 1.3 m above the east rim of the deflation basin and has a WNW-ESE (285–105°) orientation. The windward face is shorter and steeper (from 15 to 21°), the leeward side is longer and gentler (less than 10°), and the southern arm is slightly higher than the northern arm (Fig. 2b). Within the deflation basin, both the western wall and the bottom are covered by *Artemisia Frigida* and *Corispermum*, with vegetation coverages of 10% and 25%, respectively; the lee side of the depositional lobe is covered by *Cleistogenes squarrosa* with 20% coverage; and the grassland around the blowout is covered by *S. grandis*, *Stipa krylovii Roshev* and *L. chinensis*, with about 40% vegetation coverage.

3. Material and methods

3.1. Soil compaction

The compaction of the surface sand (0–10 cm depth) was measured using a Field Scout SC900 Soil Compaction Meter (Spectrum Technologies, USA). The measurement units are kPa, and the measurement range of the instrument is 0–7000 kPa. Nineteen points within the blowout were selected and each was measured three times to produce an average.

3.2. Wind flow measurements

A series of wind flow direction and speed monitoring exercises were conducted within the blowout over the 6-day period from May 23 to May 28, 2014. Twenty-one anemometers and ten wind vanes were utilized to measure the wind speed and direction 0.3 m above the surface (Fig. 2c). In order to clearly define the approaching wind speed and direction, a reference tower with two anemometers (0.3 and 2.0 m) and one wind vane (2.0 m) was erected 5 m from the eastern rim of the blowout. The instruments