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Dynamics of skimming flow in the wake of a vegetation patch

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ABSTRACT

Dryland vegetation is often spatially patchy, and so affects wind flow in complex ways. Theoretical models and wind tunnel testing have shown that skimming flow develops above vegetation patches at high plant densities, resulting in little or no wind erosion in these zones. Understanding the dynamics of skimming flow is therefore important for predicting sediment transport and bedform development in dryland areas. However, no field-based data are available describing turbulent airflow dynamics in the wake of vegetation patches. In this study, turbulent wind flow was examined using high-frequency (10 Hz) sonic anemometry at four measurement heights (0.30 m, 0.55 m, 1.10 m and 1.65 m) along a transect in the lee of an extensive patch of shrubs (z = 1.10 m height) in Namibia. Spatial variations in mean wind velocity, horizontal Reynolds stresses and coherent turbulent structures were analysed. We found that wind velocity in the wake of the patch effectively recovered over ~12 patch heights (h) downwind, which is 2–5 h longer than previously reported recovery lengths for individual vegetation elements and two-dimensional wind fences. This longer recovery can be attributed to a lack of flow moving around the obstacle in the patch case. The step-change in roughness between the patch canopy and the bare surface in its wake resulted in an initial peak in resultant horizontal shear stress (τ_r) followed by significant decrease downwind. In contrast to τ_r, horizontal normal Reynolds stress ($\overline{u'^2}$) progressively increased along the patch wake. A separation of the upper shear layer at the leeside edge of the patch was observed, and a convergence of τ_r curves implies the formation of a constant stress layer by ~20 h downwind. The use of τ_r at multiple heights is found to be a useful tool for identifying flow equilibration in complex aerodynamic regimes. Quadrant analysis revealed elevated frequencies of Q2 (ejection) and Q4 (sweep) events in the immediate lee of the patch, which contributed to the observed high levels of shear stress. The increasing downwind contribution of Q1 (outward interaction) events, which coincides with greater $\overline{u'^2}$ and wind velocity, suggests that sediment transport potential increases with greater distance from the patch edge. Determining realistic, field-derived constraints on turbulent airflow dynamics in the wakes of vegetation patches is crucial for accurately parameterising sediment transport potential in larger-scale dryland landscape models. This will help to improve our understanding of how semi-vegetated desert surfaces might react to future environmental and anthropogenic stresses.

1. Introduction

The extreme nature of drylands means that semi-arid vegetation is often patchy and dynamic through time and space, due to complex relationships between plants, soil and transport processes (Meron et al., 2004; Wainwright, 2009; Bailey, 2011; Getzin et al., 2014). Vegetation elements provide drag on the overlying airflow, thus affecting wind velocity profiles and significantly complicating aeolian dynamics on desert surfaces (Ash and Wasson, 1983; Wolfe and Nickling, 1993; Wiggs et al., 1994, 1995; King et al., 2005). Shifts in vegetation structure resulting from grazing, fire and climatic changes are known to have a significant impact on the potential for sediment mobility (Li et al., 2008; Sankey et al., 2012), and therefore have important implications for landscape-scale change in many dryland systems (Thomas et al., 2005; Wang et al., 2009; Stewart et al., 2014).

Patchy dryland vegetation modulates the erodibility of the surface and the erosivity of the wind through three primary mechanisms (Wolfe and Nickling, 1993). First, vegetation can directly shelter sediment from the wind by covering a fraction of the surface and providing a lee-side wake (e.g. Al-Awadhi and Willetts, 1999; Leenders et al., 2007). Second, vegetation acts to trap windborne particles, thus reducing flux and providing loci for sediment deposition (e.g. Gillies et al., 2000, 2014; Okin et al., 2006; Davidson-Arnott et al., 2012). Finally, vegetation directly affects

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wind velocity profiles by acting as a form of roughness that results in the growth of a boundary layer downwind (Greeley and Iversen, 1985).

The impact of boundary layer growth on meso-scale erosion patterns depends strongly on the type of flow regime (Wolfe and Nickling, 1993). When isolated roughness elements populate the surface (<16% cover; Wolfe and Nickling, 1993), each plant sheds turbulent eddies by diverting windflow around and above each plant (Judd et al., 1996; Sutton and McKenna-Neuman, 2008; Suter-Burri et al., 2013; Lee et al., 2014). This increases drag, thus raising shear stress and the aerodynamic roughness (z_0), and potentially enhancing erosion locally (Ash and Wasson, 1983). An arch vortex with a reverse surface flow direction can develop directly downwind of individual elements, upwind of a flow stagnation region where the outer flow reattaches to the ground (Sutton and McKenna-Neuman, 2008; Walter et al., 2012). In wake-interference flow (c. 16–40% cover; Wolfe and Nickling, 1993), the increased drag and thus shear stress resulting from the presence of multiple elements may only be partly absorbed by the plants themselves, resulting in stress transference to the inter-canopy surface and potentially greater sediment transport (Breshears et al., 2009; Dupont et al., 2014). In the case of skimming flow (>~40% cover; Wolfe and Nickling, 1993), the increased drag from the vegetation acts to displace z_0 upwards (establishing a zero-plane displacement height, d), which simultaneously extracts momentum from the surface wind and increases wind shear stress above the canopy (e.g. Wasson and Nanninga, 1986; Gillette and Stockton, 1989; Wiggs et al., 1994; Gillies et al., 2002; Crawley and Nickling, 2003; Gillette et al., 2006; Dupont et al., 2014). The absorption of additional stresses by the plants therefore decreases the erosion potential at the surface. Fig. 1 displays the different flow regimes and their associated theoretical wake developments.

Theoretical calculations (e.g. Raupach, 1992; Okin, 2008) and experimental measurements (Minvielle et al., 2003; Leenders et al., 2007; Youssef et al., 2012; Gillies et al., 2014; Wu et al., 2015; Mayaud et al., 2016) suggest that protective wakes downwind of individual vegetation elements extend to approximately 7–10 h (where h is the height of the element). Wind dynamics in the wakes of more substantial vegetation patches, where skimming flow is in operation, are less well studied, excepting some wind tunnel studies (e.g. Burri et al., 2011; Youssef et al., 2012; Suter-Burri et al., 2013) and a few field and modelling studies of forest edges (e.g. Gash, 1986; Liu et al., 1996; Frank and Ruck, 2008). Belcher et al. (2003) provided a useful model for describing the adjustment of a turbulent boundary layer to the step-change in surface roughness represented by a forest patch, focusing mainly on the above-canopy zone. Wind tunnel and modelling experiments have also been conducted to understand flow behaviour around backward-facing steps (e.g. Le et al., 1997; Wengle et al., 2001), although these configurations often have more extensive low-velocity zones and delayed reattachment points compared to vegetated cases due to their almost parallel-to-wall streamlines. To our knowledge no field-based study has characterised flow recovery and turbulence in the wake of a real dryland vegetation patch. This is a significant gap in the literature, given the increasing evidence that high-frequency turbulence is an important driving force behind aeolian sediment entrainment and transport in the boundary layer (Butterfield, 1991; Sterk et al., 1998; Namikas et al., 2003; Schönfeldt and von Löwis, 2003; Baas and Sherman, 2005; Leenders et al., 2005; Baddock et al., 2011; Weaver and Wiggs, 2011; Wiggs and Weaver, 2012; Chapman et al., 2013).

Wind erosion models form a key part of our understanding of sediment transport dynamics on partly vegetated surfaces, and are crucial for assessing the potential vulnerability of dryland regions to soil degradation (Okin et al., 2006; Ravi et al., 2011). A wind erosion model presented by Okin (2008) recognises the inherent irregularity of vegetation patterning in drylands, and emphasises the controlling influence of the size of 'gaps' or 'corridors' in the vegetation structure. The Okin model assumes that plants are porous objects, such that surface shear velocities in the wake of plants can be greater than zero and recover asymptotically.

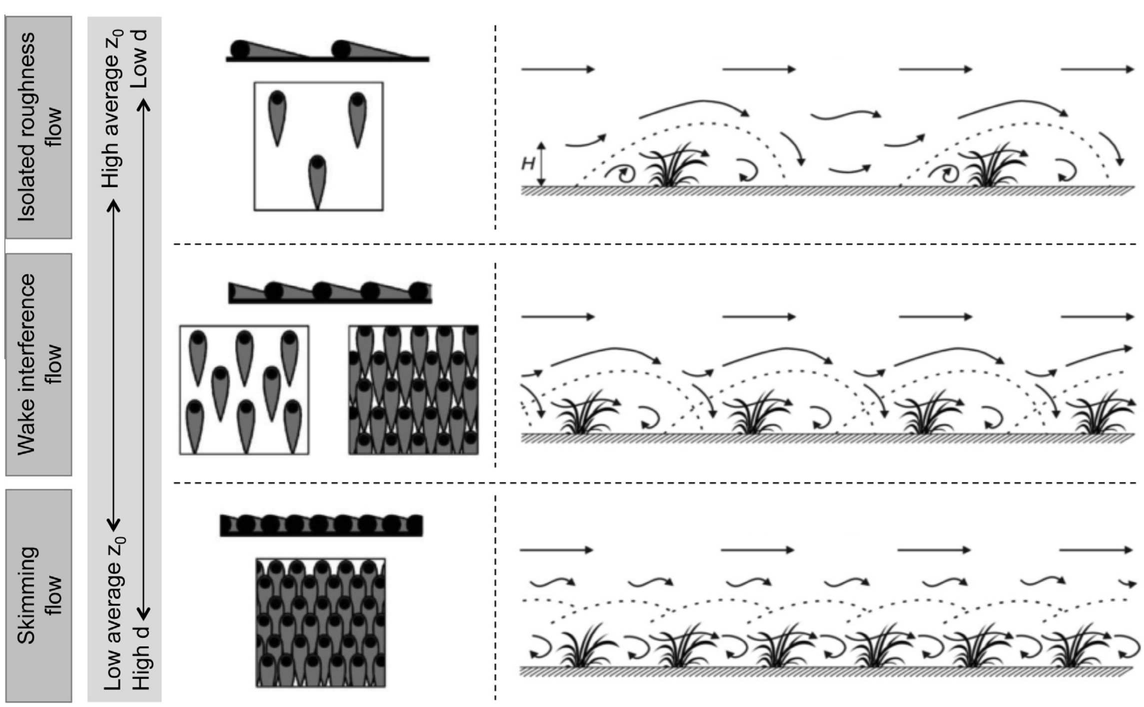

Fig. 1. Flow regimes and associated theoretical wake development, shown in schematic plan and side view. Shaded areas are wake regions. The effect of different flow regimes on average z_0 (aerodynamic roughness) and d (displacement height) per plant unit is shown (adapted from Wolfe and Nickling, 1993, p.57, and Suter-Burri et al., 2013, p. 66).