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Threshold wind velocity dynamics as a driver of aeolian sediment mass flux

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ABSTRACT

Horizontal (saltation) mass flux is a key driver of aeolian dust emission. Estimates of the horizontal mass flux underpin assessments of the global dust budget and influence our understanding of the dust cycle and its interactions. Current equations for predicting horizontal mass flux are based on limited field data and are constrained to representing transport-limited equilibrium saltation, driven by the wind momentum flux in excess of an entrainment threshold. This can result in large overestimation of the sediment mass flux. Here we compare measurements of the soil entrainment threshold, horizontal mass flux, and their temporal variability for five undisturbed dryland soils to explore the role of threshold in controlling the magnitude of mass flux. Average and median entrainment threshold showed relatively small variability among sites and relatively small variability between seasons, despite significant differences in soil surface conditions. Physical and biological soil crusts had little effect on the threshold value, and threshold appeared to play a minor role in determining the magnitude of sediment transport. Our results suggest that horizontal mass flux was controlled more by the supply limitation and abrasion efficiency of saltators present as loose erodible material or originating from neighboring soil sources. The omission of sediment supply and explicit representation of saltation bombardment from horizontal flux equations is inconsistent with the process representation in dust emission schemes and contributes to uncertainty in model predictions. This uncertainty can be reduced by developing greater process fidelity in models to predict horizontal mass flux under both supply- and transport-limited conditions.

1. Introduction

A fundamental challenge in aeolian research is to accurately predict the horizontal (saltation) mass flux for varying soils and surface conditions. In most dust emission models the horizontal mass flux (Q) is calculated independently of the vertical (dust) flux, following physically based equations that are parameterized to represent measurements of sand transport rates (e.g., Bagnold, 1937; Kawamura, 1951; Owen, 1964; Lettau and Lettau, 1978; Shao et al., 1993). In general, these equations predict that Q scales with the third power of the wind shear velocity (u_*, m s^{-1}) and the proportion of shear velocity that is in excess of an entrainment shear velocity threshold (u_{*t}). For example (after Owen, 1964):

$$Q = C\frac{\rho_a}{g}u_*^3\left(1-\frac{u_{*t}^2}{u_*^2}\right) \quad (u_* \geqslant u_{*t}) = 0 \quad (u_* < u_{*t}), \tag{1}$$

where Q has the units of kg m^{-1} s^{-1}, ρ_a is the air density (kg m^{-3}) and g is the acceleration of gravity (m s^{-2}). C is a dimensionless fitting parameter.

The equations typically follow Owen's hypotheses that (1) the saltation layer behaves as an aerodynamic roughness whose height is proportional to the thickness of the layer, and (2) the concentration of particles within the saltation layer exists in a steady state and is thus in equilibrium with the wind momentum flux incident on the bed (Owen, 1964). It has been shown that feedback between the saltation layer and aerodynamic roughness produces a convergence of velocity profiles around a focal point whose height is determined by the flux density, grain trajectories and their vertical distribution (Bagnold, 1941; Sherman, 1992; Duran et al., 2011; Jenkins and Valance, 2014). However, the assumption of equilibrium transport scaling with u_*^3 and driven solely by $u_* > u_{*t}$ is often not consistent with measurements under field conditions (Namikas and Sherman, 1995; Sherman and Farrell, 2008; Sherman and Li, 2012; Sherman et al., 2013; Rotnicka, 2013). This is a recognized source of uncertainty in transport predictions.

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Recently progress has been made to numerically resolve saltation mechanics (e.g., Werner, 1990; Creyssels et al., 2009; Kok and Renno, 2009). This work has provided insights into the feedbacks between the saltation layer and wind velocity profile over erodible and rigid beds (Duran et al., 2012; Charru et al., 2013; Jenkins and Valance, 2014). It has also been shown that the scaling of Q with u_* varies with bed hardness (Ho et al., 2011; Jenkins and Valance, 2014) and moisture content (Rotnicka, 2013), and that these surface conditions also moderate the occurrence of equilibrium or non-equilibrium saltation (McKenna Neuman and Scott, 1998; Wiggs et al., 2004). Observations suggest that saltator availability, bed hardness and saltation bombardment may have a greater effect on horizontal mass flux than u_{*t} in supply-limited systems (Gillette and Chen, 2001; Gillies et al., 2014). This appears to be consistent across the major global dust source areas (e.g., Chappell et al., 2008), but the physical mechanisms have not been fully resolved with experimental data.

Representing the effects of sediment supply limitation, bed hardness, and saltation bombardment on horizontal mass flux remains an ongoing challenge (Shao, 2008). One approach, described by Bagnold (1941) in formulating the transport equation, is to account for bed characteristics and sediment supply by modifying C in Eq. (1) (e.g., Gillette and Chen, 2001). Modifying the flux equation exponent and proportionality factor may also provide a solution for representing effects of bed hardness (Ho et al., 2011; Jenkins and Valance, 2014). However, a generalizable approach for accurately predicting Q across soil types and surface conditions has so far been elusive. While saltation bombardment and surface cohesion are explicitly represented in some dust emission schemes (e.g., Shao et al., 2011; Kok et al., 2014), approaches do not yet determine Q as a function of these processes and for supply-limited systems where the ratio u_{*t}/u_* (Eq. (1)) may not be a reliable predictor of sediment transport.

Accurately determining the soil entrainment threshold remains key to establishing the controls on timing and magnitude of horizontal mass flux in both transport- and supply-limited systems. Considerable attention has been given to determining the entrainment threshold for different soils (e.g., Gillette et al., 1980) and the effects of soil disturbance (e.g., Belnap et al., 2007). The majority of this work has been conducted using laboratory and field wind tunnel experimentation, as reviewed by Webb and Strong (2011). This work has provided insights into the potential variability in the entrainment threshold through its response to changing environmental conditions. Nonetheless, our understanding as formalized in sediment flux equations derives almost exclusively from studies that consider the role of threshold under transport-limiting conditions (e.g., Bagnold, 1937; Kawamura, 1951; Owen, 1964; Lettau and Lettau, 1978; Shao et al., 1993).

Challenges arise when translating the findings of wind tunnel studies of threshold to understand sediment flux dynamics in supply-limited settings. These include (1) unless repeated, the studies often provide snapshots of the entrainment threshold at a specific point in time, perhaps relating only to the condition of the soil surface during experimental measurements (typically lasting < 30 min) (e.g., Gillette et al., 1980), and (2) both results and interpretation are strongly influenced by the measurement scale of wind tunnels, which do not capture spatial variability in sediment supply or produce large turbulence structures that can drive sediment transport (Sherman and Farrell, 2008). The implications are that little remains known about threshold dynamics that influence the timing and magnitude of sediment transport (Barchyn and Hugenholtz, 2012). Measurements from wind tunnels, that have formed the basis of our understanding, may not always be representative of the processes driving Q in supply-limited landscapes where sparse available saltators on the soil surface or originating from neighboring surfaces (e.g., source bordering dunes) may be responsible for driving the sediment transport process (Macpherson et al., 2008). Understanding threshold dynamics at the field scale is needed as a basis for evaluating controls on horizontal mass flux and developing greater process fidelity in aeolian sediment transport models.

This paper evaluates threshold wind velocity dynamics in undisturbed supply-limited dryland landscapes. The scope of the paper is to explore, based on field measurements and our understanding of process, possible factors driving variability in Q not explained by variability in entrainment threshold. The paper objectives are to (1) evaluate the magnitude of horizontal mass flux for five undisturbed dryland soils, (2) quantify temporal variability in the threshold wind speed (U_t) at which mass flux is initiated, and (3) describe the characteristics of threshold dynamics relative to other factors that may influence sediment transport. The research aims are addressed using data from the Chihuahuan Desert of southern New Mexico, USA. We compare and contrast soil entrainment thresholds and their temporal variability among sites to examine, within the limits of the data, the significance of threshold dynamics and the implications for wind erosion modeling.

2. Methods

2.1. Site description

Five field sites were established at the Jornada Experimental Range in southern New Mexico, USA, in April 2013 (Fig. 1). The sites were selected to represent the range of soil textures and surface conditions that frequently emit dust in the region (Floyd and Gill, 2011). They are located across five vegetation/soil complexes that are typical of the northern Chihuahuan Desert, as studied by Bergametti and Gillette (2010). Plant community composition in the study area varies with soils, elevation and landscape position. The historic plant communities at the sites are C_4 grasslands or mixed communities of warm-season grasses, shrubs and half-shrubs (McClaran and Van Devender, 1997).

Site 1 is located on sandy clay loam soil (US Department of Agriculture classification) within a crusted playa surrounded by tobosa grass (*Pleuraphis mutica* Buckley) and burrograss (*Scleropogon brevifolius* Phil.). The location has an exposed bare fetch ~100 m in length and ~40 m wide extending to the southwest from the site. Site 2 is located on a loam soil within a broad (~5 ha) open playa with mixed physical and biological (cyanobacteria, lichen) soil crusts. The site is surrounded by sparse patches of burrograss ~50 m from the instrumentation. Site 3 is centered in a smaller (~2 ha), predominantly bare, playa with sandy clay loam soil surrounded by a sand ridge ~2 m high covered with dropseed (*Sporobolus* R. Br.) and creosote (*Larrea tridentata* DC). Site 4 is located on a sandy loam soil with sparse mixed cover dominated by honey mesquite (*Prosopis glandulosa* Torr.) and purple threeawn (*Aristida purpurea* Nutt.). Site 5 is also located on a sandy loam soil, supporting a diverse community including honey mesquite, black grama (*Bouteloua eriopoda* Torr.) and dropseed.

The mean annual precipitation (1915–2014) for the study area is 250 mm (coefficient of variation 35%), with 60% falling in the summer months from June through September. The mean annual maximum and minimum temperatures range from 25 °C to 5 °C (Wainright, 2006). Land surrounding the study sites is periodically grazed by cattle.