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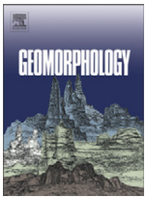

Quantifying relationships of burning, roughness, and potential dust emission with laser altimetry of soil surfaces at submeter scales

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ABSTRACT

Decrease in surface roughness by the reduction of vegetation is one mechanism by which fire can promote aeolian transport in a variety of landscapes. The extent to which fire might alter the roughness of the soil surface at fine spatial scales and the effect of this alteration on post-fire aeolian response is not well known. We examined relationships in the field between dust emissions and subcentimeter-level soil surface roughness at submeter spatial scales with a terrestrial laser scanner and portable wind tunnel analog. Based on aeolian theory, we hypothesized that observed relationships would differ from those determined in previous studies with laser altimetry at landscape scales (meter–kilometer length scales). We examined four semiarid shrublands in southern Idaho/USA containing a distinct pattern of undershrub and interspace microsites, including recently burned and unburned conditions. Mixed models were used to determine effects of burning on surface roughness and the response of dust emissions to changes in surface roughness. Results indicated that burned soil surfaces were rougher than unburned soil surfaces. Dust emissions were enhanced by increases in roughness on burned soil surfaces and in the absence of nonerodible roughness elements (i.e., plants). This finding is expectedly in contrast to previous work that demonstrated an inverse relationship between soil erosion and surface roughness determined with LiDAR (light detection and ranging) at landscape scales (vegetated and unvegetated surfaces). Relationships of LiDAR-derived roughness and aeolian emissions are scale dependent and vary with environmental factors of fire and vegetation. These findings are integral for future research that attempts to parameterize model-based predictions of aeolian emissions with LiDAR-derived roughness.

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1. Introduction

Measurements of surface roughness are necessary for model- and experiment-based predictions of aeolian emissions on earth and other planetary surfaces (King et al., 2008; Okin, 2008; Sutton and McKenna-Neuman, 2008; Maurer et al., 2010; Neakrase and Greeley, 2010; Turpin et al., 2010; Munson et al., 2011). Approaches to quantifying roughness are limited at a large geographic extent and fine spatial resolution on heterogeneous surfaces, however. Laser altimetry (i.e., light detection and ranging, LiDAR, or ground-based terrestrial laser scanning, TLS) has undeniable utility for making measurements of roughness (variability in surface elevation at millimeter–kilometer length scales), yet it is a relatively unexplored predictive tool for aeolian processes (Bullard, 2006; Baas, 2008; Hodge et al., 2009a,b; Pelletier et al., 2009; Sankey et al., 2010; Nield et al., 2011; Nield and Wiggs, 2011). LiDAR measurements of surface variability have potential utility for estimating important parameters for aeolian transport models such as aerodynamic roughness and zero plane displacement (Menenti and Ritchie, 1994; De Vries et al., 1997); yet the relationship between LiDAR-derived roughness and many fundamental aeolian processes has not yet been described (Nield et al., 2011).

Soil erosion by wind has been shown to be inversely related to roughness derived from LiDAR acquired at relatively coarse (10^1–10^3 m) geographic scales (Pelletier et al., 2009; Sankey et al., 2010). At such coarse spatial scales, aeolian erosion is expected to predominate on smooth surfaces with limited vegetation and microtopography, whereas deposition predominates on rough surfaces that are vegetated and/or have greater microtopographic relief (i.e., more nonerodible roughness elements). At finer spatial scales (e.g., 10^{-3}–10^{-1} m), the positive relationship between maximum heights achieved by saltating particles and surface roughness (Fryrear and

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Saleh, 1993) was recently characterized by LiDAR on a sand beach and additionally attributed to the hardness of the moist surface (Nield and Wiggs, 2011). Increases in surface roughness probably can enhance the aeolian emission of fine-grained dust at fine (<1 m) spatial scales and in the absence of nonerodible roughness features such as plants.

1.1. Roughness and dust relationships at submeter scales

Nonerodible roughness elements such as vegetation or rocks extract momentum from the wind and therefore reduce its erosive force. However, surface roughness can enhance dust emissions when nonerodible elements are present but at very sparse density because of increased turbulence and erosive wind flow adjacent to the roughness elements (Raupach et al., 1993; Neakrase and Greeley, 2010). Mineral dust (e.g., PM10, particles < 10 μ diameter, and/or some, though not all, larger suspension-sized grains) is often too fine to be entrained directly by wind (Bagnold, 1941; Pye, 1987). Abrasion of the surface by coarser (e.g., saltation-sized) grains and aggregates can be required to initiate emission of dust (Bagnold, 1941; Pye, 1987; Nickling, 1988; Gillete and Chen, 2001). Coarser aggregates and grains create raised roughness features on otherwise smooth surfaces that are normal, and therefore more susceptible, to the wind's erosive force (Bagnold, 1941). Coarser aggregates and grains therefore can create rougher surfaces and be a necessity for the emission of dust-sized particles.

1.2. Roughness, microtopography, fire, and dust

The relationship of dust emission and surface roughness at submeter spatial scales is especially relevant for soil surfaces with vegetation-induced microtopography, such as is characteristic of desert shrublands (Charley and West, 1975; Knight, 1994; Schlesinger et al., 1996). Microtopographic positions beneath shrub vegetation (undershrub microsites) are often raised features with lower soil bulk density, greater abundance of organic materials (ranging from undecomposed-decomposed), and more stable soil aggregates (Blackburn, 1975; Roundy et al., 1978; Wood et al., 1978, 1982; Doescher et al., 1984; Johnson and Gordon, 1988). These characteristics of undershrub microsites create a ground surface that appears rougher, with a wide range of erodible particle and aggregate sizes and densities. Shrub-interspaces, conversely, are generally slightly lower in relative elevation, less vegetated, with substantially fewer organic inputs, higher bulk density, lower aggregate stability, and greater prevalence of surfaces that appear smooth yet crusted and therefore less susceptible to erosion than undershrubs (Blackburn, 1975; Roundy et al., 1978; Wood et al., 1978, 1982; Doescher et al., 1984; Johnson and Gordon, 1988).

The roughness and morphology of desert shrublands have been previously characterized with airborne profiling (e.g., Ritchie et al., 1992) and scanning (e.g., Rango et al., 2000) LiDAR. However, to our knowledge the relationship between subcentimeter level surface roughness and dust emissions on shrub microsites has not been explicitly examined in the field. Furthermore, many desert shrublands are not susceptible to wind erosion unless the protective cover of vegetation has been removed by recent disturbance, such as fire (Sankey et al., 2009a). We therefore anticipated that burning would affect the surface roughness of microsites as well as the relationship of microsite roughness and dust emissions. For instance, the combustion of organic materials during burning might produce a more homogenous and therefore smoother surface consisting of largely mineral materials and ash. Burned surfaces are generally more erodible than unburned surfaces, however, and if erosion and roughness are positively correlated at the scale of individual microsites, it could be argued recursively that burning might increase the roughness of microsite surfaces. A possible mechanism for an increase in microsite surface roughness following burning might be that soil heating and combustion of organic materials can be spatially heterogeneous, even at fine spatial scales (i.e., beneath individual shrubs) (Seefeldt et al., 2007).

1.3. Study objectives

We studied surface roughness and dust emissions at four sites representing a range of wildland fire histories in the sagebrush steppe, a type of cold desert shrubland that is not susceptible to appreciable wind erosion unless recently burned (Sankey et al., 2009a, 2010). We examined the roughness and dust emission relationship at very fine spatial scales of shrub (sagebrush) and interspace microsites (<0.3 m diameter), in the absence of vegetation, using a TLS laser altimetry system (Clawges et al., 2007; Haubrock et al., 2009; Eitel et al., 2011) and the Portable In-Situ Wind Erosion Laboratory — a wind tunnel analog (PI-SWERL; Etyemezian et al., 2007; Sweeney et al., 2008). These tools provided a controlled and experimentally robust opportunity to examine the roughness and erosion relationship in situ, at submeter spatial scales. Four specific research questions with associated hypotheses were addressed. The first two questions pertained to microsite roughness and dust emissions, and the third and fourth questions examined elevation differences between microsites and dust emissions. Research questions and associated hypotheses were:

> Question 1: does surface roughness differ for undersagebrush and intersagebrush microsites, and what is the effect of burning? Hypotheses: (i) undersagebrush soil surfaces are rougher than intersagebrush soil surfaces, and (ii) the difference in roughness between undersagebrush and intersagebrush microsites is greater for unburned vs. burned surfaces.
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> Question 2: does dust emission potential vary with surface roughness at the microsite scale, and what is the effect of burning? Hypotheses: (i) roughness is a significant predictor of dust emissions, and (ii) dust emissions are greater on rough microsites and less on smooth microsites for burned and unburned surfaces.
>
> Question 3: what is the effect of burning on elevation differences between undersagebrush and intersagebrush microsites? Hypothesis: the difference in elevation between microsites, in which undershrubs are higher relative to adjacent interspaces, is greater for unburned vs. burned surfaces.
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> Question 4: does dust emission potential vary with elevation differences between paired undersagebrush and intersagebrush microsites? Hypothesis: elevation differences between microsite pairs are a significant predictor of dust emission potential.

2. Study area

This study was conducted in sagebrush steppe (desert shrublands) of southern Idaho (Anderson and Inouye, 2001) and the Snake River plain (SRP) at four sites during 21–24 June 2010 (Fig. 1). Each site included a wildland fire and nearby unburned location (i.e., burned and unburned treatment). Fire history at each site represented a temporal gradient; burning occurred 5 years to 2 months prior to the study (Clover fire — burned July 2005; Moonshiner fire — August 2007; Noman fire — July 2009; Samaria fire — April 2010). Unburned plant communities were primarily big sagebrush (*Artemesia tridentata*) and bunchgrasses. Vegetation on burned surfaces was predominantly crested wheatgrass (*Agropyron cristatum*) at Clover and Noman, a mix of native herbs at Moonshiner (including *Poa secunda*, *Elymus elymoides*, *Pseudoregneria spicata*, *Lappula occidentalis*, *Collinsia parviflora*), and surfaces were mostly bare at the recently burned Samaria site.