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On the prediction of threshold friction velocity of wind erosion using soil reflectance spectroscopy

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ABSTRACT

Current approaches to estimate threshold friction velocity (TFV) of soil particle movement, including both experimental and empirical methods, suffer from various disadvantages, and they are particularly not effective to estimate TFVs at regional to global scales. Reflectance spectroscopy has been widely used to obtain TFV-related soil properties (e.g., moisture, texture, crust, etc.), however, no studies have attempted to directly relate soil TFV to their spectral reflectance. The objective of this study was to investigate the relationship between soil TFV and soil reflectance in the visible and near infrared (VIS–NIR, 350–2500 nm) spectral region, and to identify the best range of wavelengths or combinations of wavelengths to predict TFV. Threshold friction velocity of 31 soils, along with their reflectance spectra and texture were measured in the Mojave Desert, California and Moab, Utah. A correlation analysis between TFV and soil reflectance identified a number of isolated, narrow spectral domains that largely fell into two spectral regions, the VIS area (400–700 nm) and the short-wavelength infrared (SWIR) area (1100–2500 nm). A partial least squares regression analysis (PLSR) confirmed the significant bands that were identified by correlation analysis. The PLSR further identified the strong relationship between the first-difference transformation and TFV at several narrow regions around 1400, 1900, and 2200 nm. The use of PLSR allowed us to identify a total of 17 key wavelengths in the investigated spectrum range, which may be used as the optimal spectral settings for estimating TFV in the laboratory and field, or mapping of TFV using airborne/satellite sensors.

1. Introduction

Threshold friction velocity (TFV) of the soil is a key parameter in quantifying soil particle movement in aeolian research, as it represents the minimum friction velocity required to initiate particle movement. For a bare soil, TFV depends on soil particle size, soil moisture, and surface crusts (Marticorena and Bergametti, 1995; Marticorena et al., 1997; Shao and Lu, 2000; Lu and Shao, 2001; Dong et al., 2002). Conventionally, TFV is estimated by experimental (e.g., wind tunnel) or modeling (e.g., empirical or theoretical) approaches. Wind tunnel can be applied *in situ* or in the laboratory, and it is able to provide a benchmark of TFV against which other methods can be compared. Depending on the soil characteristics of the study area, TFV can be quite variable over the land surface. It is difficult to estimate the spatial heterogeneity of TFV with the wind tunnel approach, as it is both time and resource intensive. These disadvantages are often more manifest at large landscape or regional scales, where extreme values for TFV have the largest impacts on aeolian sediment transport (Okin, 2005).

Alternatively, TFV may be estimated by empirical or theoretical models. A number of studies have showed that soil TFV may be parameterized as a function of the size of the in-place erodible particles (e.g., Shao and Lu, 2000; Dong et al., 2002; Cornelis et al., 2004). The particle size-based models, however, are not appropriate for field conditions as soils are a heterogeneous mixture of multiple grain size and shapes. In addition, these models fail to account for the difference between disturbed and undisturbed soils, as the disturbed soils may have the same soil texture or particle size compared to those of the undisturbed soils but much lower TFVs (Belnap et al., 2007).

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Li et al. (2010) developed an empirical method that related TFV to the resistance of the soil surface to the force of external disturbance. This approach is easy-to-use, sensitive to disturbed soil, and is able to account for the high heterogeneity of TFV. However, this approach suffers from similar disadvantage as the wind tunnel and many of the theoretical models – it is not effective for regional- to global-scale studies. Thus, a new TFV estimating method, which is able to account for the spatial heterogeneity of soil surface at appropriate spatial and temporal scales without exhaustive manual measurements, is needed.

Several studies have illustrated that soil properties, including soil texture, soil moisture, and soil crust can be quantified using reflectance spectroscopy in the visible and near infrared (VIS–NIR, 350–2500 nm) spectral regions (e.g., Okin and Painter, 2004; Kaleita et al., 2005; Xiao et al., 2006; Viscarra Rossel et al., 2006; Ben-Dor et al., 2009; Chamizo et al., 2012). For bare soils, the total reflectance increases with decreasing particle size, owing to decreased absorption and greater scattering in smaller particles (e.g., Thomasson et al., 2001). More studies have shown that the presence of physical soil crust tends to increase reflectance whereas biological crust generally decreases reflectance (Goldshleger et al., 2004; Levin et al., 2007), and the moisture content of soil also plays an important role in the measured reflectance from the soil surface (Kaleita et al., 2005).

Despite the fact that all these TFV-related soil properties have been individually studied with respect to their spectral signatures, no studies, to the best of our knowledge, have attempted to directly relate soil TFV and reflectance. Should such a relationship exist, it may be possible to use remote sensing to directly estimate TFV over large areas with high spatial and temporal resolutions. The objective of this study was to investigate the relationship between soil TFV and its spectral reflectance for a variety of soils, and to identify the best range of wavelengths or combinations of wavelengths to predict TFVs. Satellite or airborne remote sensing imagery generally consists of mixed pixels that include soil with other elements (e.g., plants, litter, etc.) that confound the direct use of remotely-sensed reflectance for observation of the soil surface. However, a critical first step in the use of remote sensing in support of aeolian studies is to show that a relationship between the governing aeolian transport parameter, TFV, has spectral correlates that can be exploited.

2. Experiment and methods

2.1. Description of the study area

The field measurements in this study were conducted at two primary locations, one is located in the Mojave Desert near Barstow, California, and the other one is located on the Colorado Plateau on lands adjacent to Moab, Utah. Field measurements were conducted during February to June 2013 when the soil surface was dry and free of snow cover. A total of 31 experimental sites were identified with 17 in the Mojave Desert and 14 in the Moab area. These experimental sites represent a range of soils, topography, and vegetation in both study areas. In this study, soils with strong physical or biological crust were not measured as these surfaces are highly resistant to erosion, and the non-spectral method used to estimate TFVs (Li et al., 2010) has not been validated on these soils.

Average annual precipitation in the Mojave Desert study area is 101 mm. An association of *Larrea tridentata* and *Ambrosia dumosa* dominates the vegetation, with minor occurrence of perennial grasses in the shrub interspaces. Soil in this location is generally sandy with high content of gravels and stones. The Moab study area has an arid climate with average annual precipitation of 229 mm. This area has a dominant shrub cover of *Sarcobatus vermiculatus* and *Atriplex canescens*, with perennial grasses of *Stipa comata* and *Hilaria jamesii* found in the shrub interspaces. Soils in this study area are dominated by sandy loam but a variety of soil textures may be found. Soils with biological or physical crusts are widely distributed in this area.

2.2. Field experiment

Field measurements were conducted at the experimental sites with relatively uniform distributions of soil and vegetation. On each of the sites, 10–15 randomly-distributed sampling locations, each has the size of approximately 5×5 cm^2, were marked out using small flags to measure soil reflectance spectra. These sampling locations were free of vegetation and rocks (diameters >5 mm). In the Mojave Desert, these sampling locations were distributed along two crossing transects (30–50 m long), with two neighboring spots separated by 2–3 m. In the Moab area, the reflectance spectra and TFVs were measured at the sampling locations located about 25 m away from the unpaved roads, and distributed parallel to the road.

Soil reflectance spectra (*R*) were measured with an ASD FieldSpec 3 portable spectroradiometer (ASD, Inc., Boulder, Colorado). All soil spectra were measured using a contact probe with a halogen light source. The spectroradiometer has a spectral resolution of 1 nm and a sampling rate of 10 Hz, with a spectral range of 350–2500 nm. A 0.30×0.30 m^2 white Spectralon™ panel (Labsphere, North Sutton, New Hampshire) was used as a 100% reflectance standard. The reflectance of the soil was calculated as the ratio of the reflected radiance of the soil to the reflected radiance of the Spectralon™ panel. On each of the 5×5 cm^2 spectral measurement locations, 10 replicated spectra readings were collected over the same target, and a total of 100–150 spectra were acquired on each of the experimental sites. The spectral measurements were conducted carefully to minimize the disturbance by the contact probe of the soil surface.

Immediately following the spectral measurement, TFVs were estimated by using a method developed by Li et al. (2010). In this method, TFV of bare soil is related to the resistance of the soil surface to the disturbance produced from an air gun and a pocket penetrometer. The TFV measurements were conducted within the 5×5 cm^2 area but not overlapped with the footprints of the spectra measurement, as the application of the spectrometer might have caused slight disturbance to the soil surface.

Finally, a soil sample from the top 1-cm was collected from within each of the 5×5 cm^2 areas. These soil samples were mixed together to form a single soil sample for an experimental site, and sent to a laboratory for texture analysis.

2.3. Soil texture analysis

In the laboratory, each soil sample was air dried and then gently crushed to break up large aggregates. Each sample was sieved using a 2-mm sieve to remove gravels and other non-soil ingredients. The relative proportion of sand (0.05–2 mm), silt (0.05–0.002 mm) and clay (<0.002 mm) content was determined using a standard hydrometer method.

2.4. Spectral data pretreatment

Spectra from each of the 5×5 cm^2 sampling locations were averaged to represent the spectra at that location, and the spectrum for an individual study site was obtained by taking the average of all spectra from all 5×5 cm^2 sampling locations. This processing resulted in one final reflectance spectrum for each experimental site.