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Threshold friction velocity of crusted windblown soils in the Columbia Plateau

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Wind erosion processes are governed by soil physical properties and surface characteristics. Erosion is initiated when the friction velocity exceeds the threshold friction velocity (u_{*t}) of soils. Although u_{*t} is influenced by soil physical properties such as wetness and crusting, there is little information available on the effect of soil crusting on u_{*t}. Knowledge of the relationship between soil crusting and u_{*t} is required to improve our ability to predict wind erosion and PM10 (particulates $\leqslant$10 μm in aerodynamic diameter) emissions from crusted soils. Threshold friction velocity was assessed on five soil types commonly found across the Columbia Plateau. These soils were obtained from agricultural fields, placed in trays, subject to various rainfall amounts to promote crust formation, and then exposed to winds inside a wind tunnel. Emission of soil particulates and PM10 as a function of wind speed were monitored by saltation and aerosol sensors. Threshold friction velocity was determined by systematically increasing wind speed until we observed an increase in airborne particulate or PM10 concentration. Threshold friction velocity increased with the development of a soil crust; u_{*t} increased exponentially with an increase in crust strength and thickness. The relationship between u_{*t} and crust thickness was influenced by clay content. The relationship between u_{*t} and crust strength and thickness should be considered when simulating wind erosion of agricultural soils.

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1. Introduction

High wind events contribute to erosion of poorly aggregated and unprotected soils within the Columbia Plateau of the Pacific Northwest United States (Saxton, 1995; Sharratt et al., 2007). Agricultural lands managed in a winter wheat-summer fallow rotation are particularly vulnerable to erosion because multiple tillage operations during the 13-month fallow phase of the rotation degrade soil aggregates and surface cover that otherwise protects soil from high winds. More than 1.5 million ha in the low precipitation zone (annual precipitation <300 mm) of the Columbia Plateau are managed in a winter wheat – summer fallow rotation. Although tillage exposes soils to high winds, this rotation has proven to be the most profitable in the low precipitation zone (Schillinger et al., 2007).

Erosion of agricultural lands can degrade both the quality of air and soil resources. For example, erosion of fine particulates at the soil surface and subsequent suspension in the atmosphere has caused road closures and traffic fatalities (Hudson and Cary, 1999) and exceedance of the National Ambient Air Quality Standards for PM10 (particulate matter $\leqslant$10 μm in aerodynamic diameter) in the Columbia Plateau (Sharratt and Lauer, 2006). Similarly, erosion of agricultural lands has contributed to the dust load of the atmosphere over Mexico City (Diaz-Nigenda et al., 2010) and eastern Australia, particularly New South Wales (Shao et al., 2007). Erosion also removes the most fertile part of the soil and causes a decline in soil productivity (Larney et al., 1998). Erosion occurs when the friction velocity (u_*) exceeds the threshold friction velocity (u_{*t}) of the surface. Friction velocity is a parameter used to describe wind shear at the surface while u_{*t} is the minimum u_* required to initiate movement of an aggregate or particle resting on the soil surface. Threshold friction velocity is influenced by soil surface water content, crusting, roughness, and biomass cover (Shao, 2000). Soil surfaces that are wet, rough, aggregated, crusted, and partially covered with crop residue generally have a higher u_{*t} than surfaces that are dry, smooth, single-grained, non-crusted, and devoid of vegetation.

Soil crusts reduce the susceptibility of the soil to erosion when exposed to wind (Chepil, 1958; Zobeck, 1991a; Zobeck and Popham, 1992; Reynolds et al., 2001). In fact, erosion of a loose

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or single-grain soil is reduced 85–98% after the formation of a crust on the soil surface (Chepil et al., 1955; Chepil, 1958; Zobeck, 1991b). Gomes et al. (2003) reported short-lived saltation and dust flux from an agricultural field after formation of a crust on a silt loam in Spain. They found saltation and dust flux only occurred in the presence of a limited supply of saltation material on the relatively strong (420–790 kPa) and thick (5–7 mm) soil crust. Surface structural crusts are formed as a result of aggregate breakdown and clay dispersion when soils are exposed to rain. Impact of raindrops also aids in compacting the surface layer. As the soil dries, a thin seal or skin forms that is less permeable than the underlying soil. This process of crust formation when soils are exposed to rain is described by Chen et al. (1980).

Although observations have been reported on the effect of rainfall characteristics on soil crust formation (Farres, 1978; Morrison et al., 1985), there is little information available on the influence of soil crusting on u_{*t}. Argaman et al. (2006) found the u_{*t} of crusted sediments was twice that of unconsolidated sediments in the Aral Sea Basin. Belnap and Gillette (1998) examined the effect of soil crust on u_{*t} in the Chihuahuan Desert of the southern United States; they reported that the u_{*t} of sandy soil with a very thin or thin crust was 30–270% higher than that of the unconsolidated sandy soil. Leys and Eldridge (1998) reported a difference in u_{*t} of about 50–150% between a crusted and non-crusted rangeland soil in New South Wales, Australia. Gillette et al. (1982) found that the u_{*t} of thin and weakly crusted sandy soils in the Mojave Desert of southern California were 8–42% higher than unconsolidated sandy soils. Ishizuka et al. (2008) reported no change in u_{*t} to initiate saltation or suspension across an agricultural field in Australia after a weak and discontinuous crust on the surface had formed as a result of a 0.2 mm rainfall event. In contrast, observations of temporal trends in particulate emissions from an eroding loessial soil in the Columbia Plateau (Sharratt et al., 2007) suggest an increase in u_{*t} in response to formation of a thin soil crust caused by 3 mm of rainfall.

Most wind erosion models account for the effect of soil crusting on the emission of particulates, but only after a certain rainfall. For example, the Revised Wind Erosion Equation (RWEQ) simulates the impact of a soil crust on wind erosion only when a soil is exposed to >12.5 mm of rainfall since the last soil disturbance (Fryrear et al., 2000). For greater amounts of rainfall, crust cover influences the maximum transport capacity in RWEQ. Similarly, the Wind Erosion Prediction System (WEPS) requires >10 mm of accumulated precipitation to form a soil crust (Hagen et al., 1995). Once a crust is formed, u_{*t} varies exponentially as a function of crust cover in the WEPS. Sundram et al. (2004) used a nondimensional index to account for a reduction in sediment discharge in response to crust formation during a high wind event in the Columbia Plateau, but did not specify the relationship between the index and crusting. Shao (2000) and Lu and Shao (2001) acknowledged the importance of soil crusting in developing an integrated wind erosion model that couples wind erosion with regional atmospheric transport, but a satisfactory relationship between u_{*t} and soil crusting was not available at the time.

Knowledge of the relationship between soil crusting and u_{*t} is required to adequately simulate wind erosion and thereby improve our understanding of the impact of land management practices and weather on erosion processes. Yet, few if any studies have been undertaken to examine the relationship between the physical properties of soil crusts and u_{*t}. The objective of this study was to evaluate the effect of soil crusting on the u_{*t} of five loessial soils of the Columbia Plateau.

2. Materials and methods

Threshold friction velocity as a function of crust strength and thickness was assessed for five soils commonly found across the Columbia Plateau of the northwestern United States. Chemical and physical properties important to crust formation of the five soils have been reported by Feng et al. (2013). These soils vary in susceptibility to wind erosion (Feng et al., 2011) and collectively cover 25% of the 65,000 km^2 area of the Columbia Plateau. The Ritzville (Coarse-silty, mixed, superactive, mesic Calcidic Haploxerolls) and Walla Walla soil series (Coarse-silty, mixed, superactive, mesic Typic Haploxerolls) are the most common series and respectively cover 10 and 6% of the Columbia Plateau. The Athena (Fine-silty, mixed, superactive, mesic Pachic Haploxerolls), Palouse (Fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls) and Warden soil series (Coarse-silty, mixed, superactive, mesic Xeric Haplocambids) each cover 3% of the region. Ritzville silt loam and Warden sandy loam are predominately found in the low precipitation (annual precipitation <300 mm) zone and are the most susceptible to erosion. Soils in the intermediate (300–450 mm annual precipitation) and high precipitation (>450 mm annual precipitation) zones have a higher PM10 composition and thus a greater potential to emit PM10 than soils in the low and intermediate precipitation zones (Chandler et al., 2004).

The five soil series were sampled at field sites across the Columbia Plateau (Fig. 1). The field sites were in a continuous crop rotation or in the fallow phase of a crop-fallow rotation. Soil was collected in late spring after sowing the continuous crop rotation or after primary tillage and rodweeding operations in the fallow year. Soil was collected from the upper 30 mm of the profile at each field site. Athena silt loam was obtained from a field near Colfax, WA (46°47′N, 117°26′W) that receives 490 mm of annual precipitation and was in a winter wheat-spring wheat-chemical fallow rotation. Palouse silt loam was obtained from a field near Pullman, WA (46°45′N, 117°12′W) that receives 540 mm of precipitation and was in a continuous cereal rotation. Ritzville silt loam was obtained from a field near Ritzville, WA (47°08′N, 118°28′W) that receives 280 mm of precipitation and was in a winter wheat-summer fallow rotation. Walla Walla silt loam was obtained from a field near Waitsburg, WA (46°15′N, 118°09′W) that receives 400 mm of precipitation and was in a winter wheat-spring wheat-summer fallow rotation. Warden sandy loam was obtained from a field near Paterson, WA (46°01′N, 119°37′W) that receives 200 mm of annual precipitation and was in a winter wheat-summer fallow rotation.

2.1. Soil preparation

After collection of soil from the field, the soil was air-dried inside a glasshouse for one week and then hand sieved through a 2-mm sieve to remove plant residue and acquire the wind erodible fraction. Aggregate and particle size distributions of the erodible fraction are reported by Sharratt and Vaddella (2012). For brevity, geometric mean diameter of aggregates was 158, 96, 67, 118, and 109 μm and mean particle size was 17.1, 21.1, 28.0, 18.5, and 77.1 μm for respectively Athena silt loam, Palouse silt loam, Ritzville silt loam, Walla Walla silt loam, and Warden sandy loam. The wind erodible fraction of each soil was added to aluminum trays (1 m long, 0.2 m wide, and 0.015 m deep) in layers. The sides of the trays were tapped to ensure even settling after the addition of each layer. Following the addition of the last layer, the trays were overfilled with soil and then leveled with a metallic screed. The resulting bulk density was about 1.1 kg m^{-3}.

Physical crusts were formed by exposing the soil to rain and then drying the soil. The trays were placed under a rainfall simulator (Bubenzer et al., 1985) for an appointed time to ensure a cumulative rainfall of 0.15, 0.3, 0.6 and 1 mm. The rainfall simulator mimics the low-intensity, small drop-size rains that are typical of the Columbia Plateau (McCool et al., 2009). The simulator was equipped with a rotating head that delivered rainfall at

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