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Controls on sediment production in two U.S. deserts

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ABSTRACT

Much of the world's airborne sediment originates from dryland regions. Soil surface disturbances in these regions are ever-increasing due to human activities such as energy and mineral exploration and development, recreation, suburbanization, livestock grazing and cropping. Sediment production can have significant impacts to human health with particles potentially carrying viruses such as Valley Fever or causing asthma or other respiratory diseases. Dust storms can cause decreased visibility at the ground level, resulting in highway accidents, and reduced visual quality in park and wildland airsheds. Sediment production and deposition is also detrimental to ecosystem health, as production reduces soil fertility at its source and can bury plants and other organisms where it is deposited. Therefore, it is important to understand how we can predict what areas are prone to producing sediment emissions both before and after soil surface disturbance. We visited 87 sites in two deserts of the western U.S. that represented a range of soil texture and surface cover types. We used a portable wind tunnel to estimate the threshold friction velocity (TFV) required to initiate sediment transport and the amount of sediment produced by the tunnel at a set wind speed. Wind tunnel runs were done before and after soil surface disturbance with a four-wheel drive vehicle. Results show that most undisturbed desert soils are very stable, especially if covered by rocks or well-developed biological soil crusts, which make them virtually wind-erosion proof. Particles at disturbed sites, in contrast, moved at relatively low wind speeds and produced high amounts of sediment. Silt was an important predictor of TFV and sediment production across all sites, whereas the influence of rock cover and biological soil crusts was site-dependent. Understanding the vulnerability of a site after disturbance is important information for land managers as they plan land use activities and attempt to mitigate the harmful effects that sediment production can have on both human and ecosystem health.

1. Introduction

Researchers have long sought to understand the interacting processes that control the entrainment, transport, and deposition of wind-borne sediments (Bagnold, 1941; Chepil, 1951, 1953; Ravi et al., 2011). Initially, this research was motivated by a desire to understand the geomorphic and erosion processes associated with agriculture (Chepil, 1951, 1953). This research has been reinvigorated as it has become clear that airborne sediments strongly influence soil fertility, planetary energy balance (Goudie and Middleton, 2001; Goudie, 2008; Ravi et al., 2011), snow surface albedo and thus melt rates on downwind mountain snowpack (Painter et al., 2010, 2012a,b). Human health and safety is of major concern, as airborne sediments can have significant impacts (Kellogg and Griffin, 2006; Griffin, 2007). Particles can carry viruses such as Valley Fever and incidences of this disease are increasing at an alarming rate in the SW United States. Many of the particle sizes can be inhaled and lodge in the lungs, causing asthma, other respiratory diseases, or even cancer. Dust storms can also cause decreased visibility, resulting in highway accidents. Airborne particles also compromise resources in areas such as National Parks, where clean air is of great value. However, as the diverse processes that control sediment emission from the micron to planetary scale are synthesized, there are frequent contradictions and uncertainties across landforms that span diverse geological and biophysical conditions.

An initial understanding of aeolian processes begins with the examination of competing forces. On one hand, aerodynamic forces from wind pick up and entrain sediment. These forces are offset by gravitational forces that inhibit movement of large particles and inter-particle forces that keep finer soil particles bound together. Because of the cohesive forces between fine particles, additional force is necessary to release sediment; sandblasting from saltating particles or compressional disturbances (e.g., vehicles) that disrupt soil aggregates are the most efficient modes of entrainment

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(Gillette, 1977; Gillette et al., 1982; Shao and Raupach, 1993). Aeolian transport typically begins after the threshold friction velocity (TFV; the minimum wind speed at which soil particles begin to detach from the soil surface; Chepil, 1951) is reached, causing saltation bombardment or the disaggregation of sand–clay aggregates (Shao, 2008). Therefore, the sediment production potential of a site is at least partially determined by the interacting dynamics of small particles that are more easily lifted and capable of being maintained as aerosols and large particles that can provide the energy necessary for entrainment (Kok et al., 2012).

Across desert regions, there are several factors that are known to increase soil resistance to wind erosion and therefore the TFV (Belnap, 2003). Soil surfaces can be covered and protected from the forces of wind by physical or biological crusts. Physical crusts are formed when soil bonds become increasingly stable as the salt, clay, or silt content of the soil increases (Chepil, 1953). Biological soil crusts (biocrusts) are soil surface communities of cyanobacteria, algae, mosses, and lichens that increase soil surface stability by binding soil particles together through the excretion of extracellular polysaccharides and mucilage associated with the rhizines, rhizoids or filaments of the various organisms (Belnap and Gillette, 1997; Marticorena et al., 1997; Barger et al., 2006; Belnap et al., 2007). Biocrusts also protect soil surfaces because many of these organisms occur above the soil, protecting the soil surface from exposure to the wind. Soil moisture also explains important short-term variability in erosion. Soil water binds particles together, increasing sediment and aggregate weight due to wet bonding forces, and water forms bridges between particles (Ravi et al., 2006). Finally, non-erodible soil surface elements including rocks, large soil aggregates, and vegetation can influence erosion rates (Gillette and Stockton, 1989; Munson et al., 2011). Disruption of any of these soil protectors can lead to increased soil vulnerability to wind erosion (Belnap and Gillette, 1997; Zender et al., 2003; Baddock et al., 2011; Munson et al., 2011).

This study addresses the broad question of how soil surface characteristics and disturbance interact to control sediment entrainment from a variety of desert substrates in the Mojave and Colorado Plateau deserts of the southwestern United States. Our general expectation, shaped by the evidence discussed above, is that the dominant control over sediment generation is the presence or absence of robust soil surface protectors. However, we expect that after accounting for the major effect of these protectors, finely resolved differences in soil texture will play an important role in explaining between-site variability in erosion potential. Therefore, we anticipate that the most erosive systems will be disturbed soils that are a mixture of small sand particles (that saltate at low wind velocities) and abundant soil fines that are easily entrained after being impacted by saltating particles. We address this question using one of the most spatially extensive and comprehensive data sets on sediment emission available. This unique dataset spans soil textures (high clay to sandy soils), desert types (hot winter-rain dominated Mojave and cool summer/winter rain dominated Colorado Plateau) and surface protectors (predominantly rocks in the Mojave Desert and for the Colorado Plateau sites, physical crusts on the Mancos Shale and biocrusts on sandstone-derived soils).

2. Methods

2.1. Site descriptions

We employed a portable wind tunnel to determine TFV and sediment production at 87 sites in the Mojave and Colorado Plateau deserts. In the Mojave Desert, we sampled 38 sites in and near Mojave National Preserve, Edwards Air Force Base, Fort Irwin National Training Center, and the Nevada Test Site before and after disturbance (hereafter termed "Mojave Desert sites"; Fig. 1). Mean annual precipitation across these sites is ~135 mm. Soils range in texture from sand to loamy sand and sandy loam with a very low level of biocrust development but high rock (particle >2 mm) cover. Vegetation at Mojave Desert sites consisted of the sparsely distributed shrubs *Larrea tridentata* (DC.) Coville and *Ambrosia dumosa* (A. Gray) Payne, with sparse annual grasses and forbs found between the shrubs. On the Colorado Plateau, we sampled 49 sites that have a mean annual precipitation of ~230 mm. Of these, 19 sites were located on soils derived from the deep marine Mancos Shale formation near Green River, UT ("Mancos Shale sites"). The sites had sandy loam, loam, and clay soils, all with poor biocrust development but robust physical crusts. Vegetation at the Mancos Shale sites consisted of sparsely distributed shrubs *Atriplex confertifolia* (Torr. & Frém.) S. Watson and *Axinella corrugata* S. Watson, with a low cover of perennial grasses and annual grasses and forbs in the shrub interspaces. Thirty additional sites were located in and near Canyonlands and Arches National Parks in southeast Utah ("Park" sites). The sites had sandy loam soils derived from sandstone parent material. All sites had well-developed biocrusts. Vegetation at these sites consisted of perennial grasses *Achnatherum hymenoides* (Roem. & Schult.) Barkworth, *Hesperostipa comata (Trin. & Rupr.) Barkworth, Pleuraphis jamesii Torr.*, and *Coleogyne ramosissima Torr.* At the Mancos sites, we collected TFV and sediment before and after disturbance. Due to regulatory constraints on off-road driving in the National Park, we only obtained TFVs for undisturbed sites.

2.2. Surface and soil characterization

A variety of soil and plant measures were taken at each site (as these data were collected over an 8 year period for different projects, not all measures were conducted at all sites; Table 1). Soil depth was determined by driving a 0.008-m diameter rod into the soil in 10 places. Biocrust measurements consisted of qualitatively assessing the level of biocrust development (level of

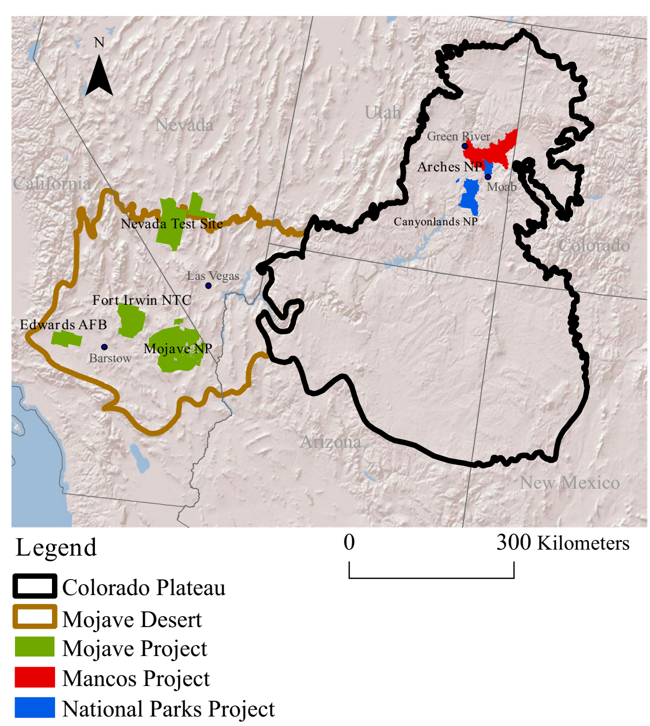

Fig. 1. Location map showing the three regions sampled in the Mojave Desert, Mancos Shale formation, and the Sandstone derived soils on the Colorado Plateau.