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Spatial and temporal patterns of dust emissions (2004–2012) in semi-arid landscapes, southeastern Utah, USA ☆

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ABSTRACT

Aeolian dust can influence nutrient availability, soil fertility, plant interactions, and water-holding capacity in both source and downwind environments. A network of 85 passive collectors for aeolian sediment spanning numerous plant communities, soil types, and land-use histories covering approximately 4000 square kilometers across southeastern Utah was used to sample horizontal emissions of aeolian sediment. The sample archive dates to 2004 and is currently the largest known record of field-scale dust emissions for the southwestern United States. Sediment flux peaked during the spring months in all plant communities (mean: 38.1 g m^{-2} d^{-1}), related to higher, sustained wind speeds that begin in the early spring. Dust flux was lowest during the winter period (mean: 5 g m^{-2} d^{-1}) when surface wind speeds are typically low. Sites dominated by blackbrush and sagebrush shrubs had higher sediment flux (mean: 19.4 g m^{-2} d^{-1}) compared to grasslands (mean: 11.2 g m^{-2} d^{-1}), saltbush shrublands (mean: 10.3 g m^{-2} d^{-1}), and woodlands (mean: 8.1 g m^{-2} d^{-1}). Contrary to other studies on dust emissions, antecedent precipitation during one, two, and three seasons prior to sample collection did not significantly influence emission rates. Physical site-scale factors controlling dust emissions were complex and varied from one vegetation type to another.

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1. Introduction

Drylands cover approximately 41% of the earth's surface (Reynolds et al., 2007a). These regions are sensitive to alterations in climate and land-use patterns (Asner and Martin, 2004; Reynolds et al., 2007a), particularly because these types of changes cause large, rapid, and irreversible transitions from stable to highly degraded ecosystems (Bestelmeyer, 2006; Bestelmeyer et al., 2011; Webb and Strong, 2011). Wind erosion drives dryland transitions by removing key nutrients and reducing the water-holding capacity of soils (Neff et al., 2005; Li et al., 2007), potentially reducing ecosystem productivity. Changes in soil properties and vegetation cover can interact synergistically with wind erosion, leading to increased desertification and greater soil erosion (Okin et al., 2006, 2009). Dryland expansion can have far-reaching impacts on aeolian transport and deposition to downwind systems at landscape, regional, and global scales (Webb and Strong, 2011). Sediment transported from drylands reduces visibility in protected National Parks and wilderness airsheds (Kavouras et al., 2007), contributes to traffic accidents (Ashley and Black, 2008), alters snow chemistry (Rhoades et al., 2010), accelerates the rate of snowmelt (Painter et al., 2007), and fertilizes distant ecosystems with nutrients (Chadwick et al., 1999; Reynolds et al., 2001; Lawrence et al., 2010). Recent anthropogenic driven changes to North American drylands have been linked to increases in dust and nutrient deposition in both the San Juan Mountains of southern Colorado (Neff et al., 2008) and the Uinta Mountains of northern Utah (Reynolds et al., 2010). Only a few studies have measured field-scale dust emissions over large areas and simultaneously quantified the effects of vegetation, ground cover, and weather patterns on sediment flux (Gillette and Pitchford, 2004; Belnap et al., 2009; Bergametti and Gillette, 2010; Reheis and Urban, 2011).

Vegetation is the most important factor in protecting soil surfaces, as bare soil alone offers very little protection from wind erosion (Belnap and Gillette, 1998; Okin, 2008). Vegetation also influences patterns of wind erosion at multiple scales, from the individual plant up to the large-scale spatial distribution of various

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plant communities (Okin et al., 2006). Plants diminish the shear stress of wind on the surface by reducing wind momentum and by trapping particles in their entrainment area (Okin et al., 2006; Floyd and Gill, 2011). The type and amount of plant cover can affect the severity of wind erosion: high perennial grass cover, higher woody plant cover, and higher average plant height all correspond to lower erosion rates in drylands (Breshears et al., 2009). Other studies indicate that shrubland communities dominated by different species exhibit highly variable erosion rates (Gillette et al., 2004; Bergametti and Gillette, 2010; Floyd and Gill, 2011), suggesting that vegetation type interacts with other factors to protect soils from wind erosion.

Characteristics of surfaces and soils variably affect the severity of wind erosion at spatial scales of centimeters to meters. More heterogeneous or "rough" surfaces diminish potential erosion compared to flatter ones by extracting momentum from wind; woody debris, plant litter, gravel, and rocks all increase soil surface roughness (Herrick et al., 2005; Okin et al., 2006). Soil aggregation is also an important aspect of site erodibility, as particles that are physically bound together by plant roots, soil organic matter, and micro-organisms are more resistant to erosion (Tisdall, 1996; Herrick et al., 2001; Roose and Barthe, 2002). Biological soil crusts (BSC), a complex association of lichen, moss, and cyanobacteria, are particularly important to drylands as they bind soil particles together, increase soil fertility by fixing nitrogen, and can cover as much as 70% of the surface in certain areas (Belnap and Gillette, 1997; Belnap et al., 2003; Chaudhary et al., 2009). The BSC effectively stabilize otherwise barren soil surfaces in plant interspaces in many semi-arid and arid landscapes. Thin, non-biological ("physical") soil crusts may also form when soil minerals, as soluble salts in Mancos shale derived soils, cement fine-textured particles together (Godfrey et al., 2008; Carpenter and Chong, 2010). Soil stabilizing crusts, however, are particularly sensitive to human land-use activities and can take decades to recover from disturbance (Belnap and Eldridge, 2001; Reynolds et al., 2006; Neff et al., 2005; Belnap et al., 2007).

Short and long-term climate patterns can influence dryland erosion processes by interacting with and affecting vegetation and soil-surface characteristics (Bach et al., 1996; Okin and Reheis, 2002; Ravi and D'Odorico, 2005; Urban et al., 2009). Dry winters in the Sonoran and Mojave deserts can inhibit subsequent plant growth, thus leading to more dust storms (MacKinnon et al., 1990; Bach et al., 1996; Urban et al., 2009). Alternatively, heavy precipitation causes increased dust emission from wet, saline playas by loosening salted surfaces (Reynolds et al., 2007b) or by providing freshly erodible sediment in alluvial flats (McTainsh et al., 1999). Soil-moisture variability, related to precipitation patterns, can affect wind-erosion potential as wetter soils tend to be more cohesive and thus have higher erosion thresholds (McTainsh et al., 1998; Ravi and D'Odorico, 2005). The link between aeolian sediment movement and high wind speeds has long been known (Bagnold, 1941), and subsequently studied in great detail (Shao, 2008). Peak wind speeds vary regionally, but tend to occur more frequently during certain time periods (Goudie and Middleton, 1992; Prospero, 2002) and can interact with land-use related disturbances to produce large quantities of atmospheric dust (van Donk et al., 2003; Belnap et al., 2009.

A large portion of aeolian research has focused on quantifying dust emission from un-vegetated "hot spots" such as Owens Lake and the Bodélé depression (Gillette et al., 2004; Koren et al., 2006), which are landscapes that produce large amounts of dust relative to their area (Gillette, 1999). Numerous studies have also investigated the causes of wind erosion in sand dunes (Namikas, 2003), un-vegetated dry or ephemeral lakes or "playas" (e.g. Gillette et al., 1997; Reheis, 2006; Reynolds et al., 2007b) or agricultural fields (Bielders et al., 1999). Only more recently have studies begun to quantify dust dynamics on partially vegetated surfaces, both disturbed (Belnap et al., 2007, 2009; Reheis and Urban, 2011) and undisturbed (Gillette and Pitchford, 2004; Bergametti and Gillette, 2010; Floyd and Gill, 2011; Sweeney et al., 2011). While the literature is expanding, the contribution of partially vegetated drylands to regional and global dust cycles is still uncertain (Okin et al., 2011). In particular, there are relatively few data on the timing, sediment flux, and spatial variability of dust emission on the Colorado Plateau in the American West.

The main objective of this study was to measure aeolian sediment emission rates across various plant communities and land-use histories across southeastern Utah. We examine how sediment flux varies with sampling season, land-use history, and plant community. We also evaluate how physical site characteristics and weather patterns control sediment flux, and explore the interactions of these variables. We sampled field-scale sediment emissions from June 2004 to October 2012 in five different plant communities on both sandstone- and shale-derived soils, and also explored the relation between land-use history and aeolian dust emission at three sets of sites on soils derived from Mancos Shale.

2. Methods

2.1. Description of study area

Sediment-flux measurements were conducted over a large area of southeastern Utah (Fig. 1), near Moab, Utah, from June 2004 to December 2011. This portion of the Colorado Plateau is a semi-arid desert that receives 215 mm of precipitation annually (measured in Moab, UT), with as much as 40% of the precipitation occurring during summer monsoons from July to September (Fig. 2). Mean annual temperatures range from a high of 20.2 °C to a low of 3.7 °C in Moab, Utah (Western Regional Climate Center, http://www.wrcc.dri.edu/summary/climsmut.html). Prevailing wind direction is generally south to southwesterly. Prolonged, high-speed wind events generally occur during the spring, from April to June (Fig. 2). Wind strength is typically weaker throughout the rest of the year but is punctuated by high-speed winds associated with convective storms during summer monsoons.

Eighty-five individual sites were established in a variety of plant communities, soil types, and land-use histories (Fig. 1; Table 1). This physiographic section of the central Colorado Plateau is characterized by nearly horizontal sedimentary rocks consisting of sandstone, siltstone, limestone, and shale bedrock units (Huntoon et al., 1982). Our study sites were located primarily on soils derived from low-elevation Mancos Shale and high-elevation Kayenta Sandstone. Elevation among sites ranges from 1300 to 2100 m above sea level. Steep sided mesas dominate the higher elevation areas and are associated with exposures of Entrada, Kayenta, Navajo, and Cedar Mesa sandstone formations where 50 sites were located. Rolling hills, narrow ridges, and broad valleys derived from Mancos Shale, comprising one-seventh of the Upper Colorado River Basin (Carpenter and Chong, 2010), typify the lower elevation terrain ~50 km to the north of Moab, UT where 28 sites were located. Eight additional study sites were established in the Badger Wash Research Area located just outside of Mack, CO (100 km northeast of Moab, UT). Badger Wash is a small, 770 ha watershed that has similar soil and topographic conditions to other Mancos sites; however, livestock have been excluded from grazing the watershed since 1953.

Study sites encompassed a wide variety of plant communities characteristic of the area, and are described by the dominant plant species present at times of field survey (>25% total cover). Pinyon–Juniper woodlands (*Pinus edibulus* and *Juniperus osteosperma*), sagebrush shrublands (*Artemisia tridentata*), blackbrush and

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