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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.
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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, rhiozoids 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

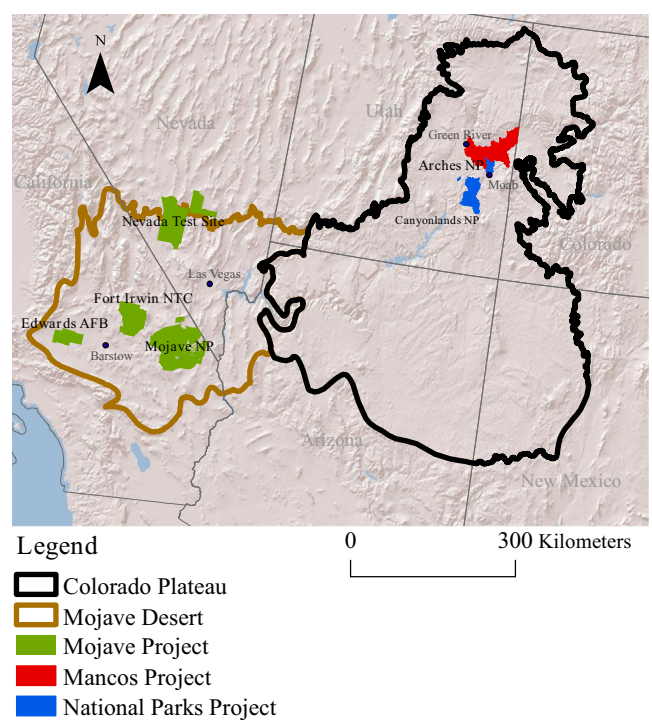

Fig. 1. Location map showing the three regions sampled in the Mojave Desert, Mancos Shale formation, and the Sandstone derived soils on the Colorado Plateau.

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Table 1
Site Characteristics for Areas Sampled in Three Regions of the Western United States.

Parameter	Mojave			Mancos			Colorado Plateau – sandstone		
	Mean	STE	Range	Mean	STE	Range	Mean	STE	Range
Control TFV (m s^{-1})	1.20	0.07	1.74	1.52	0.08	1.31	1.65	0.15	2.96
Disturbed TFV (m s^{-1})	0.35	0.03	0.89	0.44	0.05	0.77	na	na	na
Δ TFV (m s^{-1})	−0.85	0.06	1.37	−1.08	0.08	1.41	na	na	na
Control sediment production (g m^{-2} s^{-1})	0.2	0.04	1.0	0.5	0.1	1.0	na	na	na
Disturbed sediment production (g m^{-2} s^{-1})	1.8	0.4	10	5.1	1.0	17	na	na	na
Δ Sediment production (g m^{-2} s^{-1})	1.6	0.3	8.8	4.6	1.0	18	na	na	na
% Very coarse sand	13	1.9	49	0.6	0.1	1.7	0.1	0.03	0.7
% Coarse sand	11	1.2	30	0.8	0.1	2.0	0.2	0.04	1.0
% Medium sand	17	2.1	56	3.3	0.8	12.1	6.2	0.8	22
% Fine sand	24	1.7	39	20	3.1	39	42	1.4	29
% Very fine sand	14	1.0	25	20	1.8	29	24	1.2	22
% Total sand	75	1.9	42	48	3.2	44	70	0.7	16
% Clay	7.6	0.6	20	21	1.9	36	15	0.3	8.4
% Silt	17	1.7	39	31	2.2	34	15	0.7	13
Slake test – shallow	na	na	na	3	0.5	6	5	0.3	5
Slake test – deep	na	na	na	1	0.2	4	na	na	na
ug Chlorophyll/g of soil	3.1	0.8	20	6.1	0.9	14	12	1.2	25
Soil depth (m)	na	na	na	0.33	0.38	0.54	na	na	na
% Roughness	na	na	na	8.4	0.9	15	na	na	na
% Moss cover	na	na	na	na	na	na	0.2	0.2	0.0
% Lichen cover	2.4	1.0	27	na	na	na	4.0	1.4	35
Level of darkness	na	na	na	na	na	na	3.7	0.2	5.0
% Plant cover	19	1.6	39	na	na	na	na	na	na
% Rocks smaller than 2 mm	0.1	0.01	0.2	na	na	na	na	na	na
% Rocks greater than 1 mm	0.5	0.04	0.9	na	na	na	na	na	na
% Rocks greater than 9 mm	0.2	0.02	0.5	na	na	na	na	na	na
% Rocks greater than 2 mm	21	2.7	72	na	na	na	na	na	na
% Rocks between 2–50 mm	33	2.7	61	na	na	na	na	na	na
% Rocks greater than 50 mm	4.8	1.0	23	na	na	na	na	na	na

darkness, LOD; Belnap et al., 2008) and quantitatively estimating the lichen and moss cover in 0.5 × 0.5 m frames using point hits. Perennial vegetation cover was also estimated inside these frames using Daubenmire cover classes. Wet soil aggregate stability was measured (Herrick et al., 2001) at 0–0.01 m (shallow) and 0–0.1 m (deep) depths. Soil surface roughness was measured by placing a 0.2 m metal chain on the soil surface and recording the length of chain required to span roughness elements introduced by the presence of physical crusts and biocrusts. Roughness was designated as the ratio of the chain length on the rough surface relative to its original length and was used as an indicator of biocrust development. We did not assess the dry strength of physical crusts, as there are no reliable methods for doing this in the field, although their presence or absence was visually observed and recorded. Rock cover was estimated using a line-intercept method along a 1 m transect within the tunnel footprint and results aggregated into three size classes (<2 mm, 2–50 mm, and >50 mm). Each soil sample was a composite of 30 cores taken at 0–0.01 m. Texture analysis was performed using the hydrometer method (Gee and Bauder, 1979) and particles divided into size classes according to the standard USDA classification system (clay <2um, silt >2um–0.5 mm, sand >0.5 mm). For several of our analyses (noted below) the medium, coarse, and very coarse sand fractions were pooled. In order to estimate the biomass of cyanobacterial and green algae in the biocrusts, chlorophyll *a* concentrations were extracted from soil samples and determined using a spectrophotometer (Beymer and Klopatek, 1992).

2.3. Wind tunnel measurements

Measurements were taken during the years 2000–2007. The operation of the open-bottomed wind tunnel followed the procedure described in Marticorena et al. (1997). Sites were chosen based on the presence of relatively undisturbed soil conditions (herafter referred to as "control" sites) and an adjacent area that could be driven over with a vehicle to create a disturbance (hereafter referred to as "disturbed" sites). Once a site was selected, a 0.2 × 2.5 m vegetation-free area to be sampled by the wind tunnel was cleared of loose debris and the wind tunnel gently placed over the soil surface such that the soil surface was not disturbed. Wind speed in the tunnel was gradually increased until particles were observed breaking from the soil surface and traveling down the wind tunnel corridor or, on the disturbed sites, when particles began to move down the corridor; this was defined as the TFV. Once the TFV was reached, the wind speed was held constant and two complete sets of measurements were made with a Pitot tube at heights above the soil surface spaced logarithmically apart from 0.001 to 0.102 m. Speed inside the wind tunnel was then increased to a constant speed of 11.8 m s^{-1} at 0.102 m off the ground and run for a total of three minutes. The finer sediments eroded from the soil surface were collected on a filter (Air Filter Corporation, Ultra 8) that captured >90% of particles less than 3 um; the filter was located at the end of the wind tunnel. Because it was impossible to fully extract captured sediments from the filter, pre-run weights were subtracted from post-run weights to obtain the mass of fine sediments collected within the filter. Coarser sediments were collected in front of the filter, sieved through a 2-mm sieve to remove any plant litter, animal scat, and small rocks from the sample and then weighed on a balance accurate to 0.001 g. Sediment weights obtained from the filter and the material in front of the filter were added to obtain the total particle mass moved by the tunnel, hereafter referred to as "sediment mass" or "sediment produced". Total sediment mass was converted to g m^{-2} s^{-1} using the footprint of the wind tunnel (0.5 m^{-2}) and the duration of each run (180 s).

2.4. Disturbance treatment

Following the measurement of control TFV and sediment yield, we made two passes (forward and back over the same track) with a

four-wheel drive Chevrolet Suburban vehicle (weighing 2040 kg) with knobbed tires in an area immediately adjacent to the control site. Vehicles not only compact soils; their passage also disrupts protective covers on the soil surface by breaking up physical and biological crusts, crushing plants, and pushing rocks under the soil surface. In addition, vehicle acceleration flips and stirs soil, leaving particles lying loose at the surface. After passage by the vehicle, the tunnel was moved to the disturbed area and TFV and sediment production were then measured (Belnap and Gillette, 1997).

2.5. Statistical methods

Wind speed profiles in the wind tunnel were used to solve for TFV and aerodynamic roughness height according to:

$$U = \frac{U_*}{k} \ln \frac{z}{z_0}$$

where U is mean wind speed at height z, k is von Karman's constant (set to 0.4), U_* is TFV, and z_0 is aerodynamic roughness height.

All statistical analyses were performed in R (Team, 2011). Data were assessed for assumptions of normality, independence, and equal variance. Paired t-tests were used to assess the difference in mean TFV and sediment mass collected between control and disturbed sites. ANOVAs were used to assess the difference in means of TFV and sediment mass between soil types and regions. These results were compared with results from a Kruskal–Wallis test for non-parametric data and Levene's test was used to assess the assumption of equal variances of the response variables among soil types (Fox and Weisberg, 2011). A post hoc Tukey's Honestly Significant Difference was used to assess comparisons between groups of soil type and also between disturbance levels. In the case of the data from the Mancos shale, we removed one outlier based on field notes and confirmation from outlier tests from the outliers package in R (Komsta, 2011). We built predictive models of TFV, sediment mass, and the degree of change following disturbance (control values minus disturbed values) using site level characteristics with a regression tree approach in R (rpart package; Therneau and Atkinson (2012)). To test for potential multi-collinearity between explanatory variables, we first assessed correlation between explanatory variables and ran the regression tree models with and without highly correlated variables included. The final trees with and without correlated variables were identical. Pruning of trees was done by minimizing the cross validation error and allowing each explanatory variable to only be present on one branch of the tree. It should be noted that the soil textures used in these models were those of soils at the site, not those of sediments collected by the tunnel.

3. Results and discussion

As expected, there was substantial variation in soil textures across our three sampled regions (Fig. 2). The mean sand content of the Mojave (75%) and Park (70%) sites was much higher than the Mancos sites (48%), and thus the finer fraction (silt + clay) content of the Mancos sites was much higher than the Mojave or Park sites (Table 1; Fig. 2). Before disturbance, visual assessment verified that all Mancos sites had well-developed physical crusts. Visual and quantitative assessments verified Mojave sites had well-developed physical crusts and/or rock cover and all Park sites had a high cover of well-developed biocrusts.

3.1. Threshold friction velocity

Control soils, all covered with well-developed protective surfaces (physical crust, biocrust, or rocks) showed high TFVs and thus were very stable surfaces. There were no significant differences among TFVs from the regions, despite having different soil protectors: Mojave Desert TFVs averaged 1.21 m s^{-1}, Mancos Shale sites averaged 1.52 m s^{-1}, and Park sites averaged 1.65 m s^{-1} (Table 1, Fig. 3). There were also no differences in TFV among soil texture classes at the undisturbed sites in each region, except TFVs on coarse sandy soils in the Mojave were higher than those on Mojave sandy soils. Disturbance caused a significant decrease in TFV at all sites when compared to the adjacent controls (Fig. 3). Within the

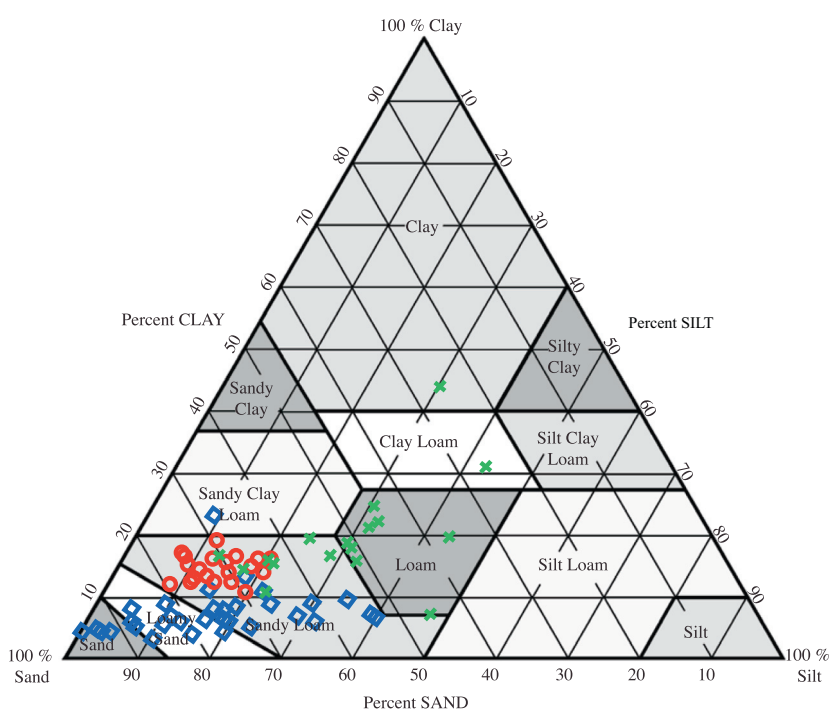

Fig. 2. Ternary plot showing textures (percent sand, silt, and clay) of surface soils (<2 mm fraction) from the three regions in this study.

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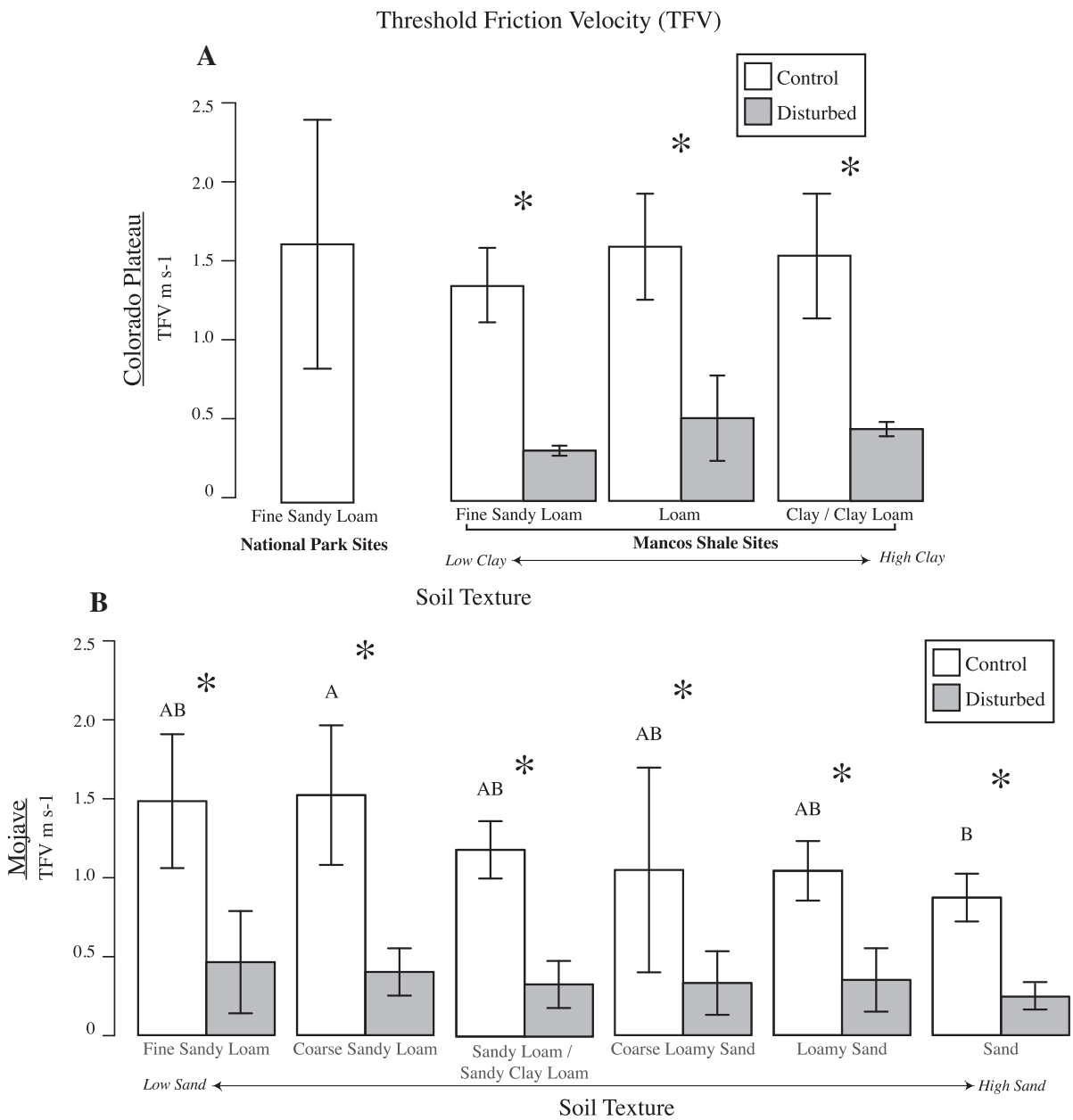

Fig. 3. Mean ± standard error of threshold friction velocity (TFV, m s^{-1}) for plots before (open bars) and after (dark bars) vehicle disturbance separated by USDA soil texture class. A significant difference between control and disturbed plots is indicated by an asterisk ($P < 0.05$). Bars sharing letters are not significantly different for control measurements ($P > 0.05$). (A) Colorado Plateau sites and (B) Mojave Desert sites. There were no significant differences between texture classes for TFV on disturbed treatments in the Mojave desert sites. There were no disturbance comparisons made on the sandstone derived soils at the sites in the National Parks.

disturbed sites, there was no difference in TFVs among surfaces once covered by the different types of soil surface protectors (physical crusts at Mancos sites, rock cover at Mojave sites) or the various soil texture classes.

We used regression tree analysis to elucidate what measured site factors were most responsible for obtained TFVs. Trees were rooted by region and disturbance class. (Factors controlling responses could vary among sites, as not all measures were performed at all sites (Table 1)). For the control sites, the primary control for TFV in both the Mancos and Mojave sites was the percent silt in soils at the site, with the more stable sites containing more silt and the least stable sites less silt (Fig. 4A and B). At the Mojave sites, stability was also conferred by a low cover of very coarse rocks (>50 mm). The difference in TFV between the high and low values was over 1 m s^{-1} and represented a doubling of TFV values. The Park sites were very different from the Mancos and Mojave sites, as the primary control on stability was chlorophyll *a* concentrations, indicative of the robust biocrusts found at these sites (Fig. 4C). Stability was also dependent on clay contents >14.4%. The highest and lowest TFV values at these sites showed more than a fourfold difference.

Vehicle disturbance dramatically lowered TFVs and completely altered the controlling factors at all sites. At the Mancos sites, the highest TFV for disturbed sites (0.63 m s^{-1}) was half that of the least stable control site (1.31 m s^{-1}) (Fig. 4D). At the disturbed Mancos sites, the most stable sites had deep (>0.39 m) soils. Post-disturbance Mojave sites showed the greatest stability where there was >35% cover of rocks over 9 mm (Fig. 4E).

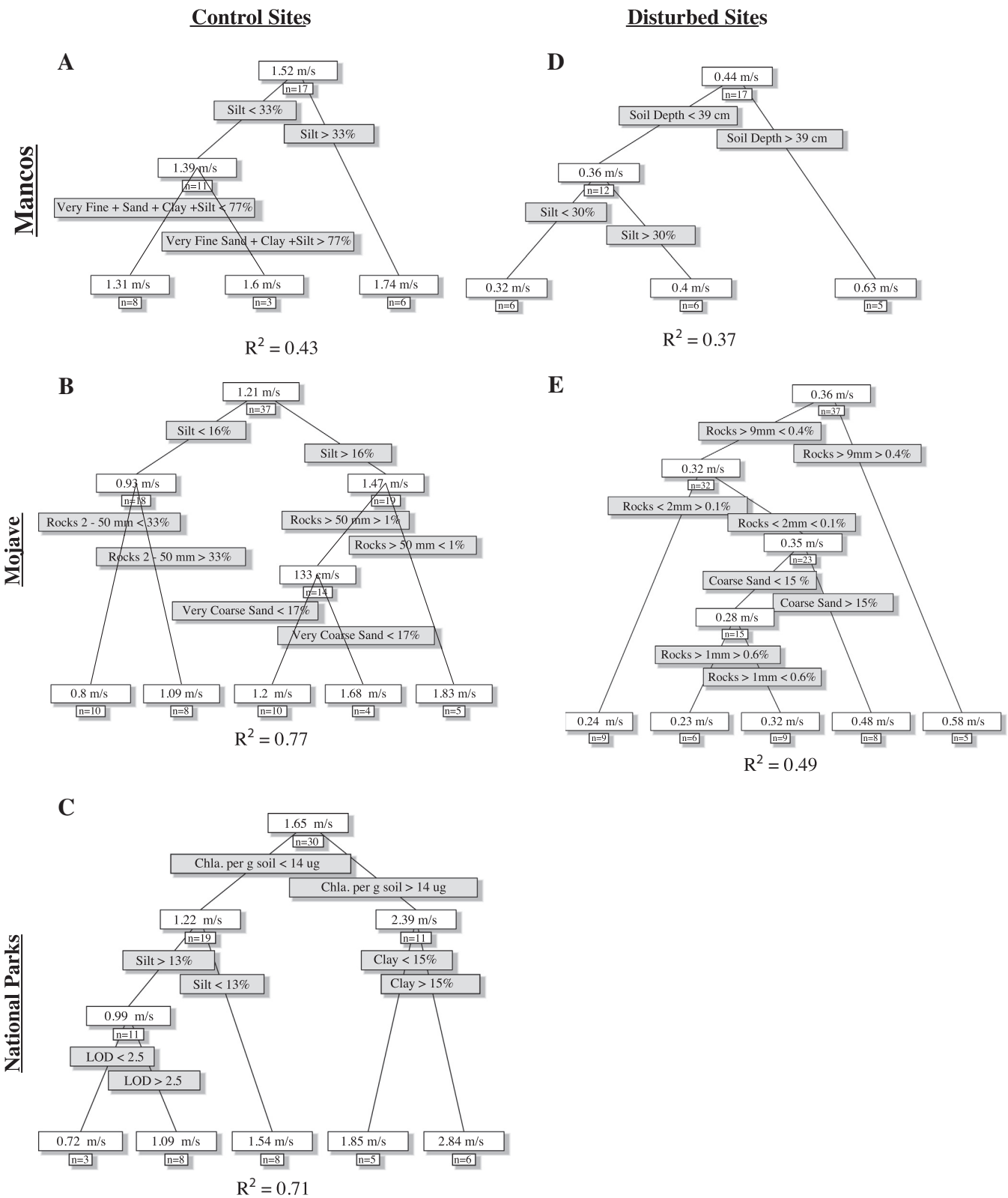

Fig. 4. Regression tree diagrams for threshold friction velocity (TFV, m s^{-1}) for control and disturbed sites. The root of each partition shows the mean value for that condition. Each branch indicates the condition under which the data are divided. The number in the box below the value indicates the number of sites under which the conditions were true. (A) Mancos Shale sites that have not been disturbed. The initial partition occurs based on silt percentage. (B) Mancos Shale sites that have been disturbed. The initial partition occurs based on soil depth. (C) Mojave Desert sites that have not been disturbed. The initial partition occurs based on silt percentage. (D) Mojave Desert sites that have been disturbed. The initial partition occurs based on the rock content above 9 mm. (E) Sandstone derived soils on the Colorado Plateau that have not been disturbed. The initial partition is based on chlorophyll *a* concentrations.

3.2. Sediment production

Very little sediment was produced at any of the control sites in any desert or on any soil type (Fig. 5). Average sediment produced for Mojave sites was 0.04 g m^{-2} s^{-1}, while Mancos Shale control sites produced 0.5 g m^{-2} s^{-1} (Table 1). There were few differences within the deserts, with the exception that the Mojave loamy sand sites produced significantly higher (0.57 g m^{-2} s^{-1}) sediment than the other soil types (0.03–0.18 g m^{-2} s^{-1}) except sandy soils (0.36 g m^{-2} s^{-1}). Disturbance significantly increased sediment production at all sites when compared to the control sites. The biggest difference between control and disturbed soils at the Mancos sites occurred on loams and fine sandy loam soils and in the Mojave, on loamy sands and sandy soils. Overall, sites on the Mancos produced significantly more sediment than did sites on the Mojave in both control and disturbed conditions.

Regression tree analysis showed that the texture of the substrate was the primary control over sediment production from the Mancos and Mojave control sites (Fig. 6A and B). For Mancos sites, soils with low clay (<23%) and high medium sand (>4%) produced the greatest sediment (78 g), while sites with high clay soils (>23%) had very low sediment production (8 g). At the Mojave sites, sand and rock content were the primary delimiters. Sites with >20% medium sand and low rock content (<6% of rocks >2 mm) produced 69 g of sediment. The lowest sediment producing sites (0.09 g m^{-2} s^{-1}) had low amounts of medium (<20%) and fine (<28%) sands.

Similar to TFV measurements, vehicle disturbance dramatically increased sediment generation at all sites and changed the controlling factors (Fig. 5; Fig. 6C and D). At the Mancos Shale sites following disturbance, sites producing the most sediment had less very fine sand (<16%), whereas sites producing the least sediment had higher very fine sand and low very coarse+ coarse++ medium sands (<5%). For Mojave sites, medium sand, as with the control sites, was still the initial delimiter. Post disturbance sites producing the least sediment had lower medium (<23%) and fine (30%) sands; sites with higher medium sand and clay contents <6% produced the most sediment.

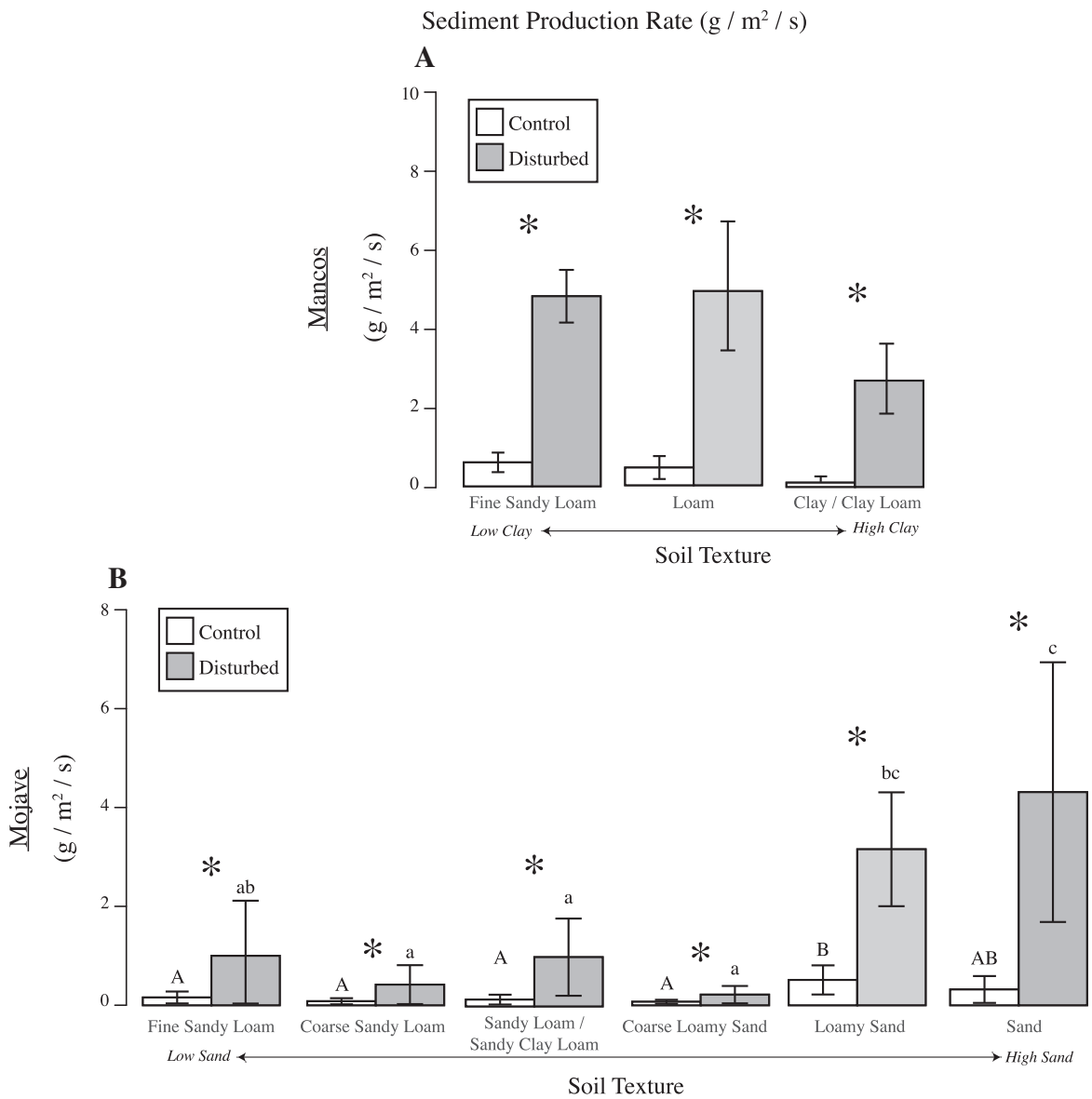

Fig. 5. Mean ± standard error of sediment produced for plots before (open bars) and after (dark bars) vehicle disturbance, separated by USDA soil texture class. A significant difference between control and disturbed plots is indicated by an asterisk ($P < 0.05$). Significant differences between soil texture classes within control or disturbance are indicated by different letters. (A) Colorado Plateau sites arranged with increasing clay content to the right and (B) Mojave Desert sites arranged with increasing sand content to the right.

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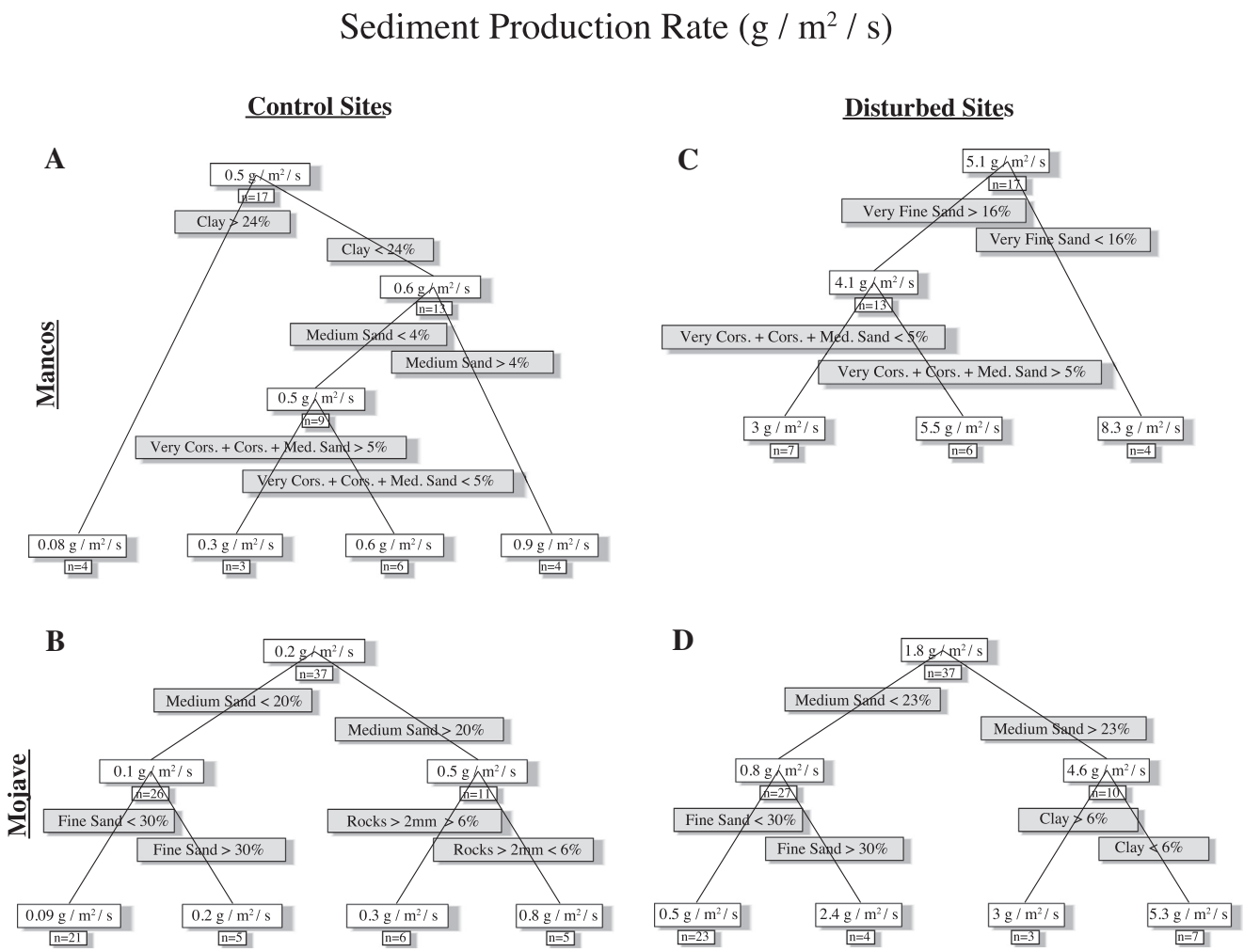

Fig. 6. Regression tree diagrams for sediment mass after the wind tunnel was run at 11.8 m s^{-1} at 0.102 m off the ground for a total of three minutes for control and disturbed sites. The root of each partition shows the mean value for that condition. Each branch indicates the condition under which the data are partitioned. The number in the box below the value indicates the number of sites under which the conditions were true. (A) Mancos Shale sites that have not been disturbed. The initial partition occurs based on clay percentage. (B) Mancos Shale sites that have been disturbed. The initial partition occurs based on very fine sand, with further divisions based on other sand fractions. (C) Mojave Desert sites that have not been disturbed. The initial partition occurs based on sand percentage. (D) Mojave Desert sites that have been disturbed. The initial partition occurs based on sand content, with further divisions based on clay and fine sand content.

4. Discussion

4.1. Threshold friction velocity

Our results show that where well-developed biocrusts (defined by a minimum chlorophyll *a* level of 0.01 mg g^{-1} soil) occur, they provide extremely high soil stability (Park sites). Previous studies show similar results (Van den ancker et al., 1985; Marticorena et al., 1997; Belnap et al., 2007). In this study, the cyanobacterially-dominated biocrusts resisted wind speeds of at least 3.48 m s^{-1}; Belnap and Gillette (1997) found TFVs up to 3.1 m s^{-1} in cyanobacterial biocrusts in this same area, with a nearby heavily lichenized crust having a TFV of up to 4.6 m s^{-1}. All TFV values are well above surface shear that produce saltation and sediment emission in the spring (Marticorena et al., 1997; Belnap and Gillette, 1997), meaning these soils are virtually wind erosion-proof. Our results also demonstrated that soil texture can secondarily influence TFV in heavily biocrusted soils, as soils with well-developed soil crusts but low clay contents had much lower TFV values than those with higher clay content, likely due to the clays contributing to robust physical crusts as well. In general, biocrusts with high biomass can be found in areas of low evapotranspiration rates (e.g. the Colorado Plateau), soils with a low shrink-swell clay component, and/or infrequent soil surface disturbance.

In contrast, biocrusts with low biomass do not impart sufficient stability to withstand high winds. A previous study in the Mojave Desert found chlorophyll *a* concentrations, and thus biocrust biomass, below the threshold to impart resistance to wind erosion (Belnap et al., 2007). A study by Belnap and Gillette (1997) in the Chihuahuan desert showed, TFVs for thin cyanobacterial crusts were 0.46 m s^{-1}. Similarly, TFVs in the current study dipped to 0.52 m s^{-1} at sites with low chlorophyll *a* values (Fig. 4). Low biocrust biomass can result from natural conditions (hot deserts with very low rainfall such as lower elevations in the Mojave Desert) and high shrink–swell clay soils (e.g., Mancos Shale), but most often are associated with high or repeated soil surface disturbances from activities such as grazing and off-road vehicles (Belnap, 2003).

Biological soil crusts are not the only important protective soil surface in desert systems. Our results clearly show this, as many control soils in the Mojave and Mancos Shale had high TFV and low sediment production, but chlorophyll *a* concentrations were below the level where there would be a biologically-mediated resistance to wind erosion (Belnap et al., 2007). Instead, physical

crusts (Mancos) or rock cover (Mojave) likely played an important role (Skidmore and Layton, 1992; Eldridge and Leys, 2003). However, as we did not have an adequate way to assess physical crust strength in the field, we relied on soil texture as a surrogate for physical crusts at the control sites and made the assumption that the shear and compressional forces applied by our vehicular disturbance treatment would disrupt them. Clay is typically considered the most important particle size class in physical binding of soil because it readily forms aggregates and, after drying following a rainfall, high clay soils readily form a physical crust with high cohesion (Chepil, 1953; Ishizuka et al., 2008). Certainly, clay concentration emerged in a number of our models, but it was the silt fraction that was most closely correlated with TFV. Silt was the first delimiter in our regression trees for control sites in the Mojave and Mancos, with high silt closely correlated with high TFV values. This is likely partially due to smaller particles being held more tightly together by van der Waals and electrostatic forces than larger particles (Iversen and White, 1982) and the propensity of smaller particles to form strong physical crusts that we visually observed in both deserts (Hillel, 1998). Unlike clays, silts do not have strong shrink-swell characteristics and would be more likely to form a cohesive physical crust under wetting and drying conditions.

As has been shown in previous studies, particle size distributions are insufficient to explain differences in sediment emissions (Sweeney et al., 2011), as protective surfaces are often the controlling factor. Compressional and shear forces associated with vehicle or animal traffic can substantially disrupt the stabilizing abilities of the protective biocrusts, physical crusts, or rock covers. In this study, we observed the same effect: our experimental vehicular disturbance caused large decreases in TFV and increases in sediment production. Reductions in TFV averaged 0.85 m s^{-1} in the Mojave and 1.08 m s^{-1} on the Mancos. While the change in TFV was similar for these two systems following disturbance, the Mancos sites produced three times higher sediment, on average, than the Mojave sites following disturbance, likely due to the larger fraction of easily entrained material in the Mancos soils.

Other studies have shown similar effects of disturbance on site TFV: Belnap and Gillette (1997) found TFV decreased 73–92% when moderate disturbance was applied to a sandy soil. In Australia, moderate disturbance reduced soil TFV by 57% in a loamy soil and by 40% in sandy soils (Leys and Eldridge, 1998). Williams et al. (1995) removed biocrusts from silty soils, decreasing TFV by 50%. Belnap and Gillette (1998) found foot or vehicle traffic on heavily biocrusted soils immediately reduced TFVs from 4.3 m s^{-1} to as low as 1.1 m s^{-1}, leaving soils highly vulnerable to wind erosion.

Rock cover likely increased TFV at the Mojave sites by protecting the surface and consuming wind momentum (Marticorena et al., 1997). Other non-erodible surface elements, such as vegetation, can modify wind erosion potential in these deserts (Munson et al., 2011) but the wind tunnel footprint was not large enough to adequately account for its influence.

4.2. Sediment production

Our results show that soil texture, especially a combination of medium sand with smaller particles, is the main predictor of sediment produced from a site both before and after disturbance. This was not unexpected, as maximum sediment is produced when larger particles (medium or larger sand grains) are detached and saltate along the soil surface, driven by the wind. As these larger particles impact the soil surface, they detach smaller particles from the soil surface; these smaller particles are then easily entrained as sediment (Field et al., 2010). Besides providing the energy for entrainment of smaller particles, saltating particles typically constitute over half of the total sediment mass (Gillette et al., 1977) and they can even become entrained during very high wind speeds (Lawrence et al., 2010). In fact, sand sized particles are deposited on ships in the middle of the ocean and on mountain tops, as noted in the distant past by Darwin on the Beagle and currently by monitors in mountains (Lawrence and Neff, 2009). Undisturbed rock cover at Mojave sites was also important in predicting lower sediment production due to its protection of the soil surface, similar to that seen for TFVs.

Sediment production from all the control sites was extremely low. Average production from the Mancos control sites was higher than the Mojave sites (0.49 vs. 0.23 g m^{-2} s^{-1}, respectively) but these values are so low the difference is relatively meaningless. Previous wind tunnel runs, using the same methods on soils equivalent to those found at our Park sites (sandstone-derived soils with well-developed biocrusts), showed equally low sediment production from the control sites, with values ranging from <0.17 to 0.83 g m^2 s^{-1} (Field et al., 2010). Sediment collectors on undisturbed sandy sites also have similar very low annual yields (Belnap et al., 2009; Flagg et al., in this issue). World-wide, sites on a variety of soil types show very low sediment production from undisturbed surfaces in ranges similar to those reported here (reviewed in Belnap, 2003).

However, when the soil surface and its protectors are disturbed, all sites in this study showed a dramatic increase in sediment production over that of the control soils. Sites in the Mancos and Mojave showed ~10 (0.49–5.13 g m^{-2} s^{-1}) and ~8 (0.23–1.83 g m^{-2} s^{-1})-fold increase with disturbance, respectively. At sites with soils equivalent to the Park sites, the Field et al. (2010) study found vehicle disturbance increased sediment production by up to 16×. The increase in sediment production following disturbance has been found in many other studies as well. For instance, Leys (1990) showed a 5-fold increase in sediment production when a biocrusted surface was disturbed. Leys and Eldridge (1998) found a 5-fold increase in sediment loss from a loamy soil and a 4-fold increase from sandy soils when biocrusts were severely disturbed by raking. Williams et al. (1995) showed a 5-fold increase in sediment loss when biocrusts were scalped from a silty soil.

It should be noted that our sediment mass values include all particle sizes collected. Because sand is much heavier than finer particles, the mass collected is likely biased towards the sand content of the collected samples for soils with high sand content. While this may partially explain the relationship between soil texture and sediment mass collected, there are several factors to consider. First, our sites were located on a wide range of soil types (sandy, sandy loam, loamy sand, clay sandy loam, clay loam and clay), the latter of which had very low sand content. Thus, our findings of close relationships between TFV and sediment production with soil texture is not necessarily biased by large amounts of sand collected. In addition, the ecological role played by windborne sand sized particles should not be discounted as unimportant. One, sand-sized particles are important saltators; without them moving across and impacting the surface, finer-textured soils produce far less sediment. Second, sand gets trapped around nearby shrubs, increasing water infiltration, trapping plant litter and soil fines, and increasing nutrient availability. Third, blowing sand buries plant litter on the surface, increasing decomposition rates. Lastly, it is important to consider that the regression analysis was done on the soil texture found at the site, not that collected in the tunnels. Therefore, our findings maintain their importance by assisting managers in predicting what surface types are most likely to produce sediment with disturbance.

5. Conclusions

Drylands around the world are considered to naturally generate large amounts of sediment, but our data and other studies show this is generally not true unless these soil surfaces are disturbed. Instead, most undisturbed soil surfaces, unless they are barren sand dunes or soils consisting of mostly fine sands, have some form of protective surface, whether physical crusts, biocrusts, rocks, or plant cover. This is demonstrated by the high TFVs and the low amount of sediment produced from undisturbed soil surfaces, irrespective of soil texture or climatic regime in two different deserts. However, almost all these protective covers are highly vulnerable to the compressional and shear forces associated with vehicle and animal traffic. Once disturbed, the previously intact protective covers are disrupted and unable to stabilize soil surfaces; therefore, sediment generation increases dramatically at most sites. As high winds are a common occurrence in dryland regions, this destabilization often results in large dust storms originating from once stable areas. Our analysis indicates that site vulnerability to wind erosion can be predicted with some simple measurements of soil texture, crust development, and non-erodible surface elements. While there are some common controls on sediment emission across sites (e.g., silt content), other biophysical factors such as biocrust biomass and rock content are more important at the site scale. Soil surface disturbances are expected to increase in dryland regions, given the increasing demand for energy, minerals, recreational opportunities and food production. With this disturbance, sediment production is also expected to increase from the disturbed soils, with a concomitant increase in human disease and highway fatalities, as well as impacts to affected ecosystems. Therefore, understanding what site factors regulate wind erosion potential gives land managers the opportunity to better mitigate the harmful effects that sediment production has on both human and ecosystem health.

References

Baddock, M.C., Zobeck, T.M., Van Pelt, R.S., Fredrickson, E.L., 2011. Dust emissions from undisturbed and disturbed, crusted playa surfaces: cattle trampling effects. Aeolian Res. 3, 31–41.
Bagnold, R.A., 1941. The Physics of Blown Sand and Desert Dunes. Methuen, London.
Barger, N.N., Herrick, J.E., Van Zee, J., Belnap, J., 2006. Impacts of biological soil crust disturbance and composition on C and N loss from water erosion. Biogeochemistry 77, 247–263.
Belnap, J., 2003. Biological soil crusts and wind erosion. In: Belnap, J., Lange, O.L. (Eds.), Biological Soil Crusts: Structure, Function, and Management. Springer-Verlag, Berlin, pp. 339–347.
Belnap, J., Gillette, D.A.I., 1997. Disturbance of biological soil crusts: impacts on potential wind erodibility of sandy desert soils in southeastern Utah. Land Degrad. Dev. 8, 355–362.
Belnap, J., Gillette, D.A., 1998. Vulnerability of desert biological soil crusts to wind erosion: the influence of crust development, soil texture, and disturbance. J. Arid Environ. 39, 133–142.
Belnap, J., Phillips, S.L., Herrick, J.E., Johansen, J.R., 2007. Wind erodibility of soils at Fort Irwin, California (Mojave Desert), USA, before and after trampling disturbance. implications for land management. Earth Surf. Proc. Land. 32, 75–84.
Belnap, J., Phillips, S.L., Witwicki, D.L., Miller, M.E., 2008. Visually assessing the level of development and soil surface stability of cyanobacterially dominated biological soil crusts. J. Arid Environ. 72, 1257–1264.
Belnap, J., Reynolds, R.L., Reheis, M.C., Phillips, S.L., Urban, F.E., Goldstein, H.L., 2009. Sediment losses and gains across a gradient of livestock grazing and plant invasion in a cool, semi-arid grassland, Colorado Plateau, USA. Aeolian Res. 1, 27–43.
Beymer, R.J., Klopatek, J.M., 1992. Effects of grazing on cryptogamic crusts in pinyon-juniper woodlands in grand-canyon-national-park. Am. Midl. Nat. 127, 139–148.
Chepil, W.S., 1951. Properties of soil which influence wind erosion: iv. State of dry aggregate structure. Soil Sci. 72, 387–402.
Chepil, W.S., 1953. Field structure of cultivated soils with special reference to erodibility by wind. Soil Sci. Soc. Am. Proc. 17, 185–190.
Eldridge, D.J., Leys, J.F., 2003. Exploring some relationships between biological soil crusts, soil aggregation and wind erosion. J. Arid Environ. 53, 457–466.
Field, J.P., Belnap, J., Breshears, D.D., Neff, J.C., Okin, G.S., Whicker, J.J., Painter, T.H., Ravi, S., Reheis, M.C., Reynolds, R.L., 2010. The ecology of dust. Front. Ecol. Environ. 8, 423–430.
Flagg, C., Neff, J.C., Reynolds, R.L., Belnap, J., Duniway, M., in this issue. Spatial and temporal variability of fugitive dust flux from Colorado Plateau landscapes. Aeolian Res.
Fox, J., Weisberg, S., 2011. An [R] Companion to Applied Regression. Sage, Thousand Oaks, CA.
Gee, G.W., Bauder, J.W., 1979. Particle-size analysis by hydrometer – simplified method For routine textural analysis and a sensitivity test of measurement parameters. Soil Sci. Soc. Am. J. 43, 1004–1007.
Gillette, D.A., 1977. Fine particulate-emissions due to wind erosion. Trans. Asae 20, 890–897.
Gillette, D.A., Stockton, P.H., 1989. The effect of nonerodible particles on wind erosion of erodible surfaces. J. Geophys. Res. Atmos. 94, 12885–12893.
Gillette, D.A., Adams, J., Muhs, D., Kihl, R., 1982. Threshold friction velocities and rupture moduli for crusted desert soils for the input of soil particles into the air. J. Geophys. Res. Oceans Atmos. 87, 9003–9015.
Goudie, A.S., 2008. The history and nature of wind erosion in deserts. Annu. Rev. Earth Planet. Sci. 36, 97–119.
Goudie, A.S., Middleton, N.J., 2001. Saharan dust storms: nature and consequences. Earth Sci. Rev. 56, 179–204.
Griffin, D.W., 2007. Atmospheric movement of microorganisms in clouds of desert dust and implications for human health. Clin. Microbiol. Rev. 20, 459–477.
Herrick, J.E., Whitford, W.G., de Soyza, A.G., Van Zee, J.W., Havstad, K.M., Seybold, C.A., Walton, M., 2001. Field soil aggregate stability kit for soil quality and rangeland health evaluations. Catena 44, 27–35.
Hillel, D., 1998. Environmental Soil Physics. Academic Press, San Diego, CA, 771.
Ishizuka, M., Mikami, M., Leys, J., Yamada, Y., Heidenreich, S., Shao, Y., McTainsh, G.H., 2008. Effects of soil moisture and dried raindroplet crust on saltation and dust emission. J. Geophys. Res. Atmos., 113.
Iversen, J.D., White, B.R., 1982. Saltation threshold on earth, mars and venus. Sedimentology 29, 111–119.
Kellogg, C.A., Griffin, D.W., 2006. Aerobiology and the global transport of desert dust. Trends Ecol. Evol. 21, 638–644.
Kok, J.F., Parteli, E.J.R., Michaels, T.I., Karam, D.B., 2012. The physics of wind-blown sand and dust. Rep. Prog. Phys. 75, 106901.
Komsta, L. 2011. Outliers: tests for outliers. R package version 0.14.
Lawrence, C.R., Painter, T.H., Landry, C.C., Neff, J.C., 2010. Contemporary geochemical composition and flux of aeolian dust to the San Juan Mountains, Colorado, United States. J. Geophys. Res. Biogeosci. 115, 2005–2012.
Lawrence, C.R., Neff, J.C., 2009. The contemporary physical and chemical flux of aeolian dust: a synthesis of direct measurements of dust deposition. Chem. Geol.. http://dx.doi.org/10.1016/j.chemgeo.2009.02.005.
Leys, J.N., 1990. Soil crusts, their effect on wind erosion. Soil Conservation Service of N.S.W. Research Note 1/90.
Leys, J.F., Eldridge, D.J., 1998. Influence of cryptogamic crust disturbance to wind erosion on sand and loam rangeland soils. Earth Surf. Processes Landforms 23, 963–974.
Marticorena, B., Bergametti, G., Gillette, D., Belnap, J., 1997. Factors controlling threshold friction velocity in semiarid and arid areas of the United States. J. Geophys. Res. Atmos. 102, 23277–23287.
Munson, S.M., Belnap, J., Okin, G.S., 2011. Responses of wind erosion to climate-induced vegetation changes on the Colorado Plateau. Proc. Nat. Acad. Sci. USA 108, 3854–3859.
Painter, T.H., Deems, J.S., Belnap, J., Hamlet, A.F., Landry, C.C., Udall, B., 2010. Response of Colorado river runoff to dust radiative forcing in snow. Proc. Nat. Acad. Sci. USA 107, 17125–17130.
Painter, T.H., Bryant, A.C., Skiles, S.M., 2012a. Radiative forcing by light absorbing impurities in snow from MODIS surface reflectance data. Geophys. Res. Lett. 39, L17502.
Painter, T.H., Skiles, S.M., Deems, J.S., Bryant, A.C., Landry, C.C., 2012b. Dust radiative forcing in snow of the Upper Colorado River Basin: 1. A 6 year record of energy balance, radiation, and dust concentrations. Water Resour. Res. 48, W07521.
Ravi, S., Zobeck, T.M., Over, T.M., Okin, G.S., D'Odorico, P., 2006. On the effect of moisture bonding forces in air-dry soils on threshold friction velocity of wind erosion. Sedimentology 53, 597–609.
Ravi, S., D'Odorico, P., Breshears, D.D., Field, J.P., Goudie, A.S., Huxman, T.E., Li, J.R., Okin, G.S., Swap, R.J., Thomas, A.D., Van Pelt, S., Whicker, J.J., Zobeck, T.M., 2011. Aeolian processes and the biosphere. Rev. Geophys., 49.
Shao, Y., 2008. Physics and Modeling of Wind Erosion. Springer, Berlin.
Shao, Y., Raupach, M.R., 1993. Effect of saltation bombardment on the entrainment of dust by wind. J. Geophys. Res. Atmos. 98, 12719–12726.
Skidmore, E.L., Layton, J.B., 1992. Dry-soil aggregate stability as influenced by selected soil properties. Soil Sci. Soc. Am. J. 56, 557–561.
Sweeney, M.R., McDonald, E.V., Etyemezian, V., 2011. Quantifying dust emissions from desert landforms, eastern Mojave Desert, USA. Geomorphology 135, 21–34.
Team, R.D.C., 2011. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
Therneau, T.M., Atkinson, B., 2012. rpart: recursive partitioning. R package version 3.1-55. <http://CRAN.R-project.org/package=rpart>
Van den Ancker, J.A.M., Jungerius, P.D., Mur, L.R., 1985. The role of algae in the stabilization of coastal dune blowouts. Earth Surf. Proc. Land. 10, 189–192.
Williams, J.D., Dobrowolski, J.P., West, N.E., Gillette, D.A., 1995. Microphytic crust influence on wind erosion. Trans. Am. Soc. Agric. Eng. 38 (1), 131–137.
Zender, C.S., Newman, D., Torres, O., 2003. Spatial heterogeneity in aeolian erodibility: uniform, topographic, geomorphic, and hydrologic hypotheses. J. Geophys. Res. Atmos. 108, 4543.

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