

Wind erodibility of soils at Fort Irwin, California (Mojave Desert), USA, before and after trampling disturbance: implications for land management

J. Belnap,^{1*} S. L. Phillips,¹ J. E. Herrick² and J. R. Johansen³

¹ US Geological Survey, Southwest Biological Science Center, 2290 S. West Resource Blvd, Moab, UT 84532, USA

² USDA-ARS Jornada Experimental Station, New Mexico State University, Las Cruces, NM 88003, USA

³ Biology Department, John Carroll University, University Heights, OH 44118, USA

*Correspondence to: J. Belnap,
US Geological Survey, Southwest
Biological Science Center, 2290
S. West Resource Blvd, Moab,
UT 84532, USA.

E-mail: jayne_belnap@usgs.gov

[†]This article is a U.S.

Government work and is in the
public domain in the U.S.A.

Abstract

Recently disturbed and 'control' (i.e. less recently disturbed) soils in the Mojave Desert were compared for their vulnerability to wind erosion, using a wind tunnel, before and after being experimentally trampled. Before trampling, control sites had greater cyanobacterial biomass, soil surface stability, threshold friction velocities (TFV; i.e. the wind speed required to move soil particles), and sediment yield than sites that had been more recently disturbed by military manoeuvres. After trampling, all sites showed a large drop in TFVs and a concomitant increase in sediment yield. Simple correlation analyses showed that the decline in TFVs and the rise in sediment yield were significantly related to cyanobacterial biomass (as indicated by soil chlorophyll *a*). However, chlorophyll *a* amounts were very low compared to chlorophyll *a* amounts found at cooler desert sites, where chlorophyll *a* is often the most important factor in determining TFV and sediment yield. Multiple regression analyses showed that other factors at Fort Irwin were more important than cyanobacterial biomass in determining the overall site susceptibility to wind erosion. These factors included soil texture (especially the fine, medium and coarse sand fractions), rock cover, and the inherent stability of the soil (as indicated by subsurface soil stability tests). Thus, our results indicate that there is a threshold of biomass below which cyanobacterial crusts are not the dominant factor in soil vulnerability to wind erosion. Most undisturbed soil surfaces in the Mojave Desert region produce very little sediment, but even moderate disturbance increases soil loss from these sites. Because current weathering rates and dust inputs are very low, soil formation rates are low as well. Therefore, soil loss in this region is likely to have long-term effects. Published in 2006 by John Wiley & Sons, Ltd.

Keywords: biological soil crusts; cyanobacteria; desert; soil aggregate; wind erosion; soil erosion

Received 25 July 2005;
Revised 2 February 2006;
Accepted 9 February 2006

Introduction

Wind movement of soil particles occurs when wind forces overcome the ability of stabilizing factors to hold the soil surface in place. Factors that stabilize soil surfaces include vascular plant materials (both living and dead), rocks, soil characteristics (e.g. high salt or calcium carbonate content, high clay/silt content, soil aggregates), physical crusts, and the cyanobacteria, lichens and mosses found in biological soil crusts. In deserts, spaces between vascular plant cover are large, the cover of plant litter is low, and most plant roots avoid the dry conditions found at the soil surface. Thus, vegetative matter plays a lesser role in soil protection in deserts relative to other ecosystems. Rocks also protect underlying soils, but in dryland areas where rock cover is low, soils depend on physical factors and biological soil crusts for protection and thus stability (Gillette *et al.*, 1980; Musick, 1998).

Physical crusts, mostly formed in soils with high salt content and fine materials, can protect soils from wind erosion. Biological soil crusts occur on almost all soil types and can cover up to 70 per cent of the soil surface in

desert regions, and often occur on top of physical crusts (Belnap *et al.*, 2003). Polysaccharides secreted by crust organisms bind soil particles together, forming a cohesive crust on the soil surface that resists both wind and water erosion (Belnap, 2003; Belnap *et al.*, 2003). These polysaccharides also contribute to soil aggregate structure, another component critical in reducing soil erosion. Sandy soils are inherently more erodible than fine-textured soils, as they have less salt, clay and silt to enhance physical crusting and soil aggregation. Therefore, sandy soils in deserts are more dependent on rocks and biological soil crusts for surface protection than other soil types (Williams *et al.*, 1995; Leys and Eldridge, 1998).

All these soil surface protectors are highly vulnerable to the compressional and shear forces generated by off-road vehicles (e.g. four-wheel drive trucks, all-terrain vehicles, military vehicles) and to trampling by livestock and humans (reviewed in Belnap and Eldridge, 2003). Physical and biological soil crusts are crushed, rocks are pushed beneath the surface, and soil aggregate structure is lost. Once soils are destabilized, loss of soil fines can reduce site productivity, as plant-essential nutrients are often bound to fine particles, and reduce the often already low soil water-holding capacity. Worldwide, windborne sediments are rapidly increasing as human utilization of arid and semiarid lands increases (Goudie, 1978; Kovda, 1980; Tsoar and Pye, 1987).

Replacement of lost soil fines via newly weathered material is slow in deserts, due to low rainfall and infrequent freeze–thaw events (Dregne, 1983). Dust deposition, a main source of soil fines in deserts, is also quite low in most regions not immediately adjacent to large dust sources (Danin and Yaalon, 1982; Reynolds *et al.*, 2001). When soils are disturbed, loss rates may often far exceed deposition (Gillette *et al.*, 1980; Offer *et al.*, 1992; Belnap and Gillette, 1997, 1998; Reynolds *et al.*, 1998). Therefore, land managers in semiarid and arid regions have long been interested in ways to reduce soil loss. To aid in this effort, we used a wind tunnel and experimental human trampling to examine factors influencing wind erosion at Fort Irwin, California, a military tank training facility located in the centre of the Mojave Desert.

Methods

Site description

This experimental study was located on lands contained within and adjacent to Fort Irwin, near Barstow, California, USA. Average annual precipitation at the sites is 101 mm. Total precipitation during the May 1999–April 2000 experimental period was 46 mm, with 23 mm occurring during the four months immediately preceding the experiment. The dominant vegetation at all the sites was *Larrea tridentata* and *Ambrosia dumosa*.

We chose three ‘control’ sites (C1–3) that were in areas currently protected from recent military training, but that had been disturbed in the historic past (>20 years) by military manoeuvres (tanks, ground troops, wheeled vehicles). We also chose three other sites (D1–3) that had been recently disturbed (<3 years) by military manoeuvres. (However, high winds prevented measurements from being conducted at D3, one of the selected disturbed sites, and thus no data are presented for this site.) Sites were carefully matched for similar topographic position and soils. All sites were covered with cyanobacterial soil crusts, with <1 per cent lichen cover at any of the sites. No vesicular horizons were observed at or below the soil surface. Four blocks of plots were designated for sites C1, C3 and D2 and six blocks for sites C2 and D1, for a total of 24 blocks. Within each block, two plots were designated, of which one was randomly chosen for trampling and the other left untrampled. This resulted in a total of 48 plots being used for this experiment.

Ground cover and soil characterization

Ground cover measures and soil characterizations were estimated in all 48 plots. Cover of rocks (>1 mm, by size class), plant litter, soil fines (expanse of particles less than 1 mm diameter), and cyanobacteria in the interspaces between plants were estimated with eight individual line transects per plot, spaced evenly over the wind tunnel’s footprint and taken prior to wind measurement. A clear plastic ruler was placed at a 45° angle from the wind direction. The length occupied by the first 15 occurrences of any of the above variables was measured to the nearest 1 mm. This resulted in total transect length beneath the tunnel being 213–800 mm per wind tunnel footprint. For characterization of the soils at the site, ten samples of surface (0–0.5 cm) and subsurface (0–10 cm) were randomly collected from each plot and composited into one surface and one subsurface sample per plot. Surface soils were analysed for chlorophyll *a*, an indicator of cyanobacterial biomass. For this analysis, samples were kept cool and dark until they reached the laboratory. Samples were then extracted with dimethylsulphoxide (DMSO) in the dark for 45 minutes at 65 °C (Ronen and Galun, 1984), shaken, and centrifuged. The supernatant was immediately placed in a Turner Designs Inc. fluorometer,

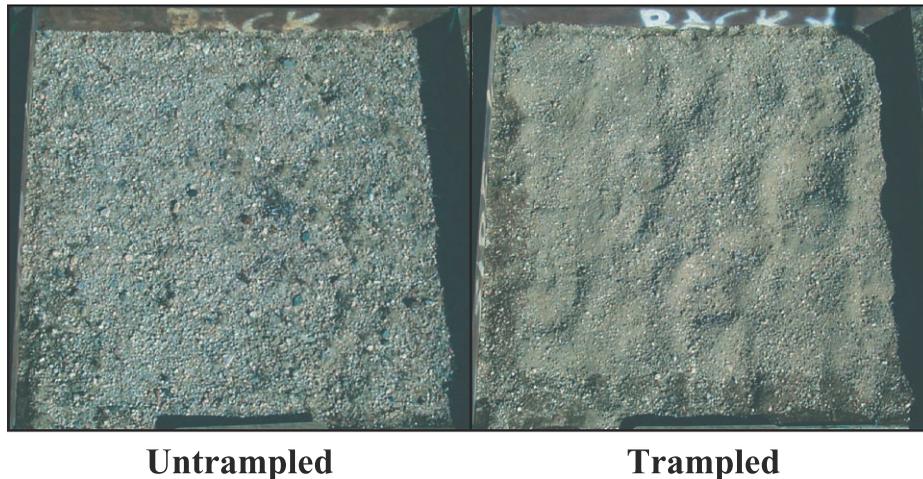


Figure 1. Photographs showing untrampled and trampled plots. This figure is available in colour online at www.interscience.wiley.com/journal/esp

where fluorescence, which is proportional to the concentration of the analyte, was measured. Fluorescence values were compared to a calibration curve obtained using commercially purchased standards of various concentrations of purified chlorophyll *a* dissolved in DMSO.

The 0–10 cm soils were analysed for soil texture. Clay was determined using the hydrometer method after dispersal with sodium hexametaphosphate (Gee and Bauder, 1986). The sand fraction was determined by washing the dispersed sample through a 53- μm sieve. Silt was determined by adding the sand and clay fractions and subtracting that total from the complete sample. The sand fraction was further divided into the following fractions by sieving for the near-surface (0–10 cm) samples: 0.05–0.1 mm, 0.1–0.25 mm, 0.25–0.5 mm, 0.5–1 mm, and 1–2 mm.

Soil stability was determined using a modified field wet aggregate stability method described in Herrick *et al.* (2001). At nine points within each plot, soil samples of uniform dimensions (2–3 mm thick, 6–8 mm on each side) were collected from the surface (0–0.3 cm deep, which included biological and physical soil crusts) and subsurface (2.0–2.5 cm deep). The collected samples were placed on a screen, soaked in water a short time, and then dipped slowly up and down in the water, with the number of dips required to break apart the sample recorded as an index of the wet aggregate stability of the sample.

Trampling

Personnel using military issue lug-soled boots applied the trampling disturbance, resulting in a churned soil surface (Figure 1). Trampling of this kind is a common disturbance type at this location and throughout the Mojave Desert. Two people (*c.* 68 kg each) jogged through the plots 50 times, with a third observer counting passes and ascertaining that the entire plot had been evenly trampled.

Wind measurements

A portable, open-bottomed wind tunnel, 150 mm \times 150 mm cross-section by 2.4 m length, was used to generate a variable-speed turbulent boundary layer over the desert surface (Figure 2; Gillette, 1978). The tunnel used a 5:1 contraction section with a honeycomb flow straightener and a roughly conical diffuser attached to the working section. Wind speed data were measured twice using a Pitot tube at seven heights (0, 0.318, 0.635, 1.27, 2.54, 5.08, 7.62 and 10.16 cm) above the soil surface, midway across the end of the working section. The Pitot tube was calibrated prior to making measurements on each plot and corrected for temperature and pressure changes each day.

The threshold friction velocity (TFV) was defined as the velocity at which fragments were initially detached from the soil surface. Wind speed inside the wind tunnel was gradually increased until forward particle movement was observable across the soil surface. The wind-flow velocity was then recorded at the soil surface and at the seven heights to create an air-flow profile. Wind speeds were then increased until surface integrity of the

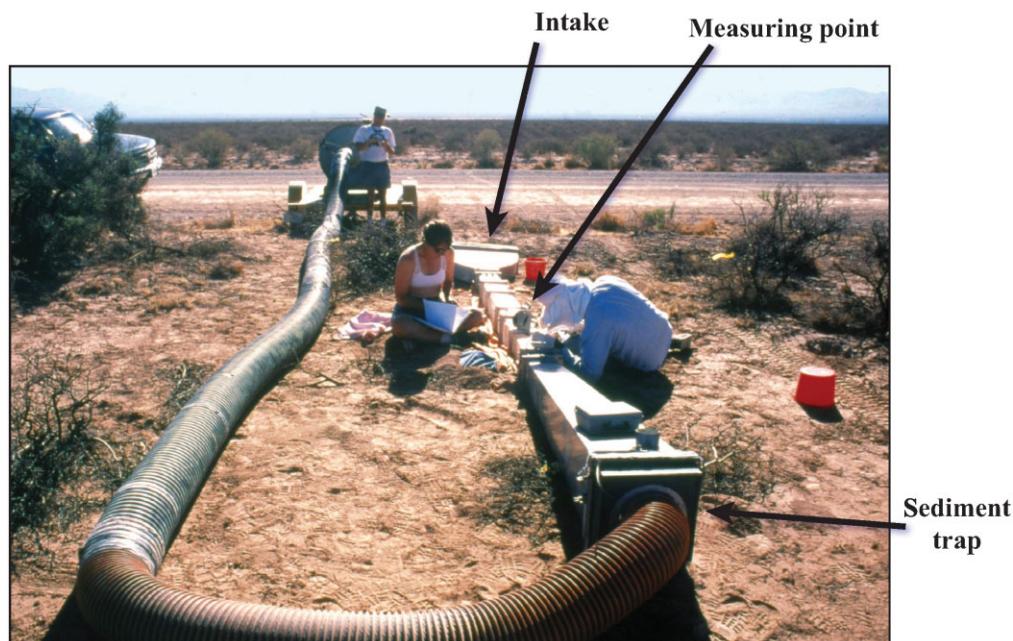


Figure 2. A photograph of the wind tunnel set-up, with arrows indicating where the air enters and where the sediment is captured. This figure is available in colour online at www.interscience.wiley.com/journal/esp

crusts was compromised, as indicated by the removal of soil particles, at which point an additional wind profile was recorded. Data for the mean horizontal wind velocity U (cm s^{-1}) versus height z (mm; wind profile data) were fitted to the function for aerodynamically rough flow (Priestley, 1959) using a non-linear least squares routine:

$$U_{*t} = kz (dU_t/dz)$$

where U_{*t} is friction velocity, and k is Von Karman's constant.

Immediately following the measurement of the final air-flow profile, the wind speed inside the tunnel was increased until air-flow velocity was 1180 cm s^{-1} . This speed represented a reasonable approximation of high spring wind speeds at this location. Wind speeds of 2300 cm s^{-1} repeatedly occur near our site (Mojave River Sink, California weather station, www.wrcc.dri.edu). However, those wind speeds are measured at 200 cm off the ground, while ours were at 10 cm off the ground. The wind tunnel was run for 3 minutes and then stopped. During this time, all the sediment blown off the soil surface was trapped in or in front of a pre-weighed fibreglass filter (with a pore size of $1 \mu\text{m}$) located at the far end of the tunnel. Following the wind tunnel run, sediment in front of the filter was collected and weighed. The pre-weighed filter was then re-weighed, and the original filter weight subtracted to obtain the weight of the sediment retained within the filter. The two sediment weights were then combined to obtain the final sediment yield value. One wind tunnel run was performed in each plot, resulting in four to six values for the experimentally applied human trampled plots and four to six values for the undisturbed plots. These four to six values were then averaged to give two mean values (newly disturbed, undisturbed) for each site.

Data analysis

Data were log-transformed to achieve normality. A mixed-effects nested design model ANOVA test was used to determine if there was a significant effect of site type (control versus recently disturbed) on TFV, chlorophyll a content, soil surface stability, and sediment production. Paired t -tests were used to determine whether there was a significant effect of trampling within a site. Spearman's rank-order correlation coefficients and linear regressions were used to test the relationship between selected soil variables and TFV or sediment production. Stepwise multiple linear regression was used to determine the factors most responsible for wind erosion at the sites. Means were considered significantly different when $P < 0.05$. All tests were done using SPSS version 12.0 (SPSS, 2003).

Table I. Texture of surface soils (0–0.5 cm) from the control and previously disturbed sites. For each variable, different letters indicate significant differences across sites at $P < 0.05$. Values are means \pm standard error

| Site | Sand (%) | Silt (%) | Clay (%) | Sand fractions (%) | | | | |
|------|------------------------------|-----------------------------|-----------------------------|------------------------------|------------------------------|------------------------------|------------------------------|-----------------------------|
| | | | | Very coarse | Coarse | Medium | Fine | Very fine |
| C1 | 86.1 \pm 0.9 ^b | 7.9 \pm 0.7 ^b | 6.0 \pm 0.4 ^{ab} | 38.4 \pm 2.4 ^c | 31.2 \pm 0.9 ^c | 16.5 \pm 1.1 ^a | 8.9 \pm 0.5 ^a | 4.9 \pm 0.3 ^a |
| C2 | 80.1 \pm 1.0 ^a | 12.8 \pm 1.0 ^c | 7.1 \pm 0.2 ^{bc} | 38.2 \pm 1.3 ^c | 27.6 \pm 0.7 ^{bc} | 16.1 \pm 0.7 ^a | 10.5 \pm 0.6 ^{ab} | 7.7 \pm 0.7 ^{ab} |
| C3 | 84.0 \pm 0.9 ^{ab} | 7.7 \pm 0.2 ^b | 8.3 \pm 0.8 ^c | 31.5 \pm 2.5 ^{bc} | 23.9 \pm 0.4 ^b | 19.4 \pm 1.1 ^{ab} | 16.4 \pm 1.1 ^{bc} | 8.8 \pm 0.3 ^b |
| D1 | 87.7 \pm 1.2 ^{bc} | 5.1 \pm 0.8 ^{ab} | 7.1 \pm 0.4 ^{bc} | 24.5 \pm 2.0 ^{ab} | 24.4 \pm 1.1 ^b | 23.1 \pm 0.7 ^{ab} | 20.1 \pm 0.3 ^c | 7.9 \pm 0.2 ^{ab} |
| D2 | 92.5 \pm 0.8 ^c | 2.7 \pm 0.7 ^a | 4.8 \pm 0.4 ^a | 18.9 \pm 2.1 ^a | 13.1 \pm 1.1 ^a | 28.1 \pm 3.7 ^b | 30.8 \pm 2.8 ^d | 9.1 \pm 1.3 ^b |

Table II. Means \pm standard error of chlorophyll *a* and soil stability values on untrampled surfaces. Chlorophyll *a* content, surface stability, and subsurface stability were all significantly higher in control compared to disturbed sites

| Site | Chlorophyll <i>a</i> ($\mu\text{g/g soil}$) | Surface soil stability (0–0.3 cm) | Subsurface soil stability (2.2–2.5 cm) |
|------|--|--------------------------------------|---|
| C1 | 3.23 \pm 0.39 | 3.8 \pm 0.5 | 3.5 \pm 0.4 |
| C2 | 4.15 \pm 0.36 | 5.7 \pm 0.1 | 2.8 \pm 0.2 |
| C3 | 2.41 \pm 1.08 | 4.9 \pm 0.4 | 1.5 \pm 0.2 |
| D1 | 0.44 \pm 0.18 | 1.6 \pm 0.1 | 1.4 \pm 0.1 |
| D2 | 0.29 \pm 0.09 | 0.4 \pm 0.3 | 1.2 \pm 0.2 |

Results

Soil texture

The disturbed sites had, on average, about 7 per cent more sand than the control sites, while having almost 6 per cent less silt (Table I). It is likely that these differences in soil texture are a result of the differential loss of silts from the recently disturbed sites via wind and water erosion.

Site effects – untrampled surfaces

Cyanobacteria crust cover could not be reliably quantified, as cyanobacterial biomass was so low it was not visually distinguishable from bare soil, and cyanobacteria also occurred under the many tiny rocks present on the soil surface. Therefore, we relied on chlorophyll measures to indicate the quantity of crust organisms present. When values for control (untrampled) sites were pooled and compared to the pooled values for recently disturbed sites, the control sites had significantly higher values than the recently disturbed sites for chlorophyll *a* (means = 3.3 versus 0.37 $\mu\text{g/g soil}$, respectively; Table II), surface soil stability (means = 4.8 versus 1.0 units, respectively; Table II), subsurface stability (means = 2.6 versus 1.3 units, respectively; Table II), TFVs (means = 423.6 versus 154.2 cm s^{-1} ; Figure 3), and rock cover (means = 63.6 versus 48.2 per cent; Figure 4). Control plots had lower sediment yield (means = 0.04 versus 0.50 $\text{g m}^{-2} \text{s}^{-1}$; Figure 5) than the recently disturbed sites. Chlorophyll *a* and surface stability were significantly related ($R^2 = 0.80$, $P < 0.001$) when all sites were pooled.

Effects of trampling

Rock cover declined at all sites except D1 after trampling (Figure 4). Because trampling destroyed the surface stability of the plots, this variable was not remeasured after disturbance. Trampling significantly decreased TFVs at all sites, except at D2, when compared to the untrampled plots (the percentage decline in TFVs at C1 = 84 per cent, C2 = 72 per cent, C3 = 50 per cent, D1 = 43 per cent). Trampling reduced TFVs to equally low levels at all sites, regardless of previous disturbance history (Figure 3). The percentage decline of TFVs caused by trampling was more pronounced at the control sites (trampled = 50 per cent reduction, untrampled = 84 per cent reduction) compared to the recently disturbed sites (trampled = 24 per cent reduction, untrampled = 43 per cent). Untrampled sites showed a positive

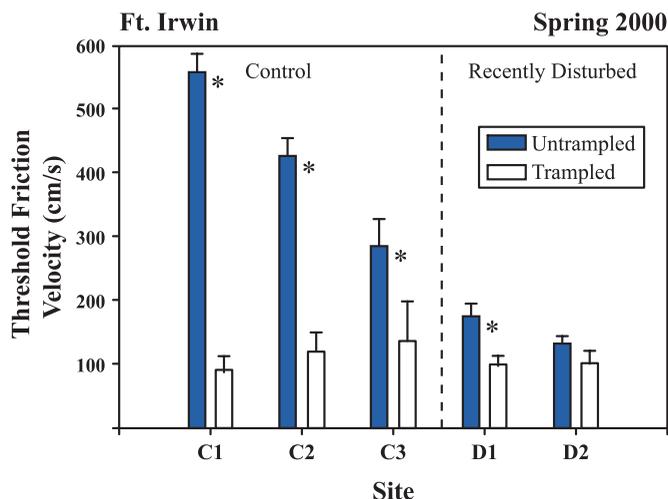


Figure 3. Mean \pm standard error of TFV before trampling (dark bars) and after trampling (light bars) at control and recently disturbed sites. Statistical comparisons were done with log-transformed values. A significant difference between untrampled and trampled surfaces at the same site is indicated by an asterisk ($P < 0.05$). This figure is available in colour online at www.interscience.wiley.com/journal/espl

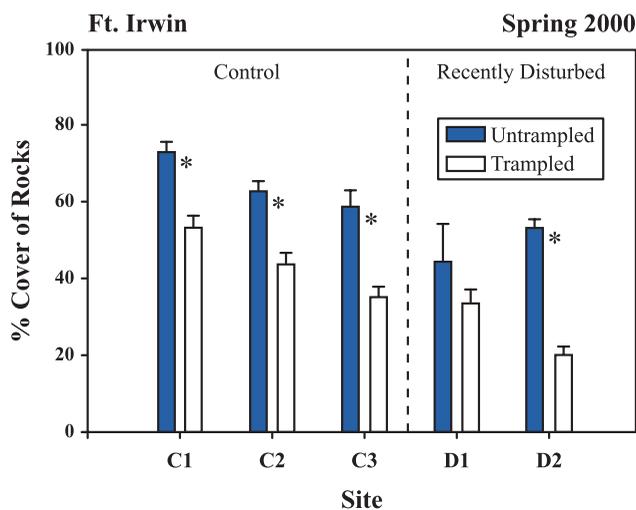


Figure 4. Average rock cover (rocks > 1 mm) before trampling (dark bars) and after trampling (light bars) at the control and recently disturbed sites. A significant difference between untrampled and trampled surfaces at the same site is indicated by an asterisk ($P < 0.05$). This figure is available in colour online at www.interscience.wiley.com/journal/espl

relationship between chlorophyll *a* and TFVs ($R^2 = 0.58$, $P = 0.01$). However, this relationship was lost immediately after trampling ($R^2 = 0.01$, $P = 0.66$).

Sediment production increased significantly with trampling at all sites except C1 (Figure 5). The amount of sediment lost with trampling from the recently disturbed training sites was much higher (trampled = 1.98 g/m^2 , untrampled = 0.50 g/m^2) than the amount lost from the control sites (trampled = 0.34 g/m^2 , untrampled = 0.04 g/m^2). A significant but low, negative relationship between chlorophyll *a* and sediment production was present, before trampling ($R^2 = 0.35$, $P < 0.0001$) and moderate after trampling ($R^2 = 0.56$, $P < 0.0001$).

Stepwise multiple linear regression analysis including all measured variables at all sites showed untrampled TFVs were best predicted by the fine sand fraction, rock cover and subsurface soil stability combined ($R^2 = 0.91$, $P < 0.034$; Table III). The TFV after trampling was weakly predicted by clay content ($R^2 = 0.27$, $P < 0.02$). Sediment yield at the untrampled sites was best predicted by the coarse and medium sand fractions and subsurface soil stability combined

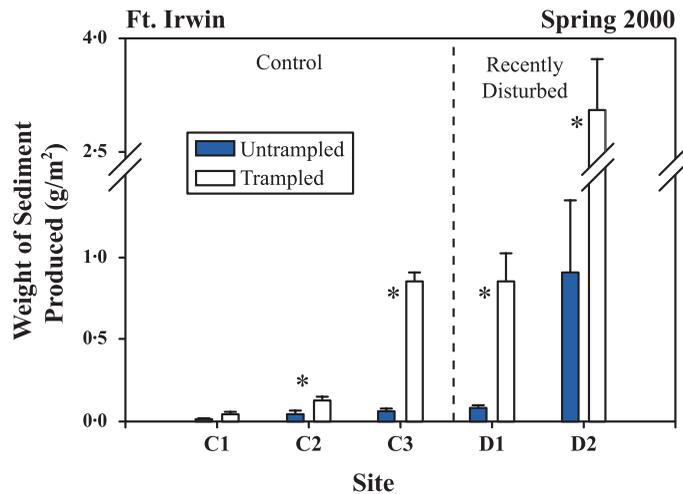


Figure 5. Mean \pm standard error of sediment produced from plots before trampling (dark bars) and after trampling (light bars) at control and recently disturbed sites. Statistical comparisons were done with log-transformed values. A significant difference between untrampled and trampled surfaces at the same site is indicated by an asterisk ($P < 0.05$). This figure is available in colour online at www.interscience.wiley.com/journal/espl

Table III. Stepwise multiple linear regression models that best predict TFVs and sediment yield among all measured variables at all sites combined

| Dependent variables | Predictors | Model coefficients | R^2 | P |
|---------------------------|------------------|--------------------|-------|---------|
| Untrampled TFV | Intercept | 284.01 | | 0.021 |
| | Fine sand | -13.95 | 0.81 | 0.001 |
| | Rock cover | 235.37 | 0.87 | 0.027 |
| | Subsurface slake | 57.73 | 0.91 | 0.034 |
| Trampled TFV | Intercept | -55.21 | | 0.43 |
| | Clay | 24.69 | 0.27 | 0.02 |
| Untrampled sediment yield | Intercept | 52.53 | | 0.67 |
| | Coarse sand | -16.86 | 0.66 | <0.0001 |
| | Medium sand | 13.74 | 0.76 | <0.0001 |
| | Subsurface slake | 71.85 | 0.88 | 0.002 |
| Trampled sediment yield | Intercept | 53.44 | | 0.50 |
| | Fine sand | 3.78 | 0.82 | 0.3 |
| | Medium sand | 3.94 | 0.86 | 0.02 |
| | Coarse sand | -5.02 | 0.90 | 0.03 |

($R^2 = 0.88$; $P < 0.002$). Sediment yield from trampled sites was best predicted by the coarse, medium and fine sand fractions ($R^2 = 0.90$), with fine sand fractions being the most important determinant ($R^2 = 0.82$).

Discussion

Polysaccharides extruded by biological soil crust organisms entrap and bind soil particles together, creating linked, large soil aggregates (e.g. Van den Ancker *et al.*, 1985; Danin *et al.*, 1989; Chartes, 1992; Belnap and Gardner, 1993; Eldridge and Greene, 1994), and moving these larger aggregates requires greater wind velocity than that required to move single soil particles (Gillette *et al.*, 1980; Marticorena *et al.*, 1997). Therefore, many studies have shown that the presence of biological soil crusts reduces soil erosion by wind (e.g. Dulieu *et al.*, 1977; Van den Ancker *et al.*, 1985; Tsoar and Møller, 1986; Danin *et al.*, 1989; Pluis, 1994; Williams *et al.*, 1995; Belnap and Gillette, 1997; Marticorena *et al.*, 1997; Belnap and Gillette, 1998; Leys and Eldridge, 1998). Even chemically killed crusts, if left undisturbed so that the polysaccharide material stays intact, appear to protect the soil surface from erosion at least in the short term (after which polysaccharide material probably degrades; Williams *et al.*, 1995). Similarly, our results show that wind erosion

decreases (as indicated by a decline in TFVs and an increase in sediment production) as biological soil crust biomass (as indicated by chlorophyll *a*) increases. Other factors can also be important in reducing wind erosion. In this study, increased rock cover, coarser soil particles, and subsurface soil stability (an indication of the inherent stability of the soil) also significantly decreased wind erosion. While physical crusts can also be important in stabilizing soils (Eldridge and Leys, 2003), we did not directly measure them and so are unable to quantitatively assess their importance at these sites.

When all factors were considered together, however, soil texture was the most important in predicting the wind erodibility of these sites. Greater amounts of fine sand in surface soils resulted in greater vulnerability to wind erosion, as it was related to lower TFV and greater sediment yield. The presence of coarse sands, on the other hand, reduced the amount of sediment produced, as coarse sand particles are large and difficult to move. This result appears to contrast with other studies on desert soils where biological crust cover and condition were the deciding factors in TFV and sediment production levels (e.g. Williams *et al.*, 1995; Belnap and Gillette, 1997, 1998).

A likely cause of this difference among studies was the amount of cyanobacteria and lichens present at the different sites. The biomass of the biological crust organisms present reflects the climate at the site, the time since past disturbance, and the severity of that disturbance. In hot deserts with very low precipitation, biological soil crusts are dominated by a low amount of cyanobacteria. The Fort Irwin sites, with a maximum of 0.006 mg chlorophyll *a* per gram soil, had close to an order of magnitude lower cyanobacterial biomass compared to many other sites in the Mojave Desert (maximum 0.046 mg chlorophyll *a* per gram soil) and sites in SE Utah (maximum 0.122 mg chlorophyll *a* per gram soil). Thus, a threshold of cyanobacterial biomass is likely required before it becomes the major determinant of site susceptibility to wind erosion. In addition, the Fort Irwin sites lacked soil lichens. Belnap and Gillette (1998) showed that lichens conferred much more stability to soils than cyanobacterial cover. This points out the importance of carefully defining the flora and biomass of biological soil crusts before broad statements are made regarding their role in stabilizing soils.

Soils are often much more susceptible to wind erosion after disturbance (reviewed in Belnap, 2003; Belnap and Eldridge, 2003). Cyanobacterial filaments, lichens and mosses are brittle when dry and crush easily under compressional or shear forces incurred by activities such as trampling or vehicular traffic. Such disturbances also crush physical crusts, subsurface soil aggregates, and the connections between aggregates, lowering the wind force required to detach particles from the soil surface. In addition, rock cover is often decreased as surface rocks are pushed below into the soil, leaving surface soils less protected (Belnap and Warren, 2002). In this study, we observed

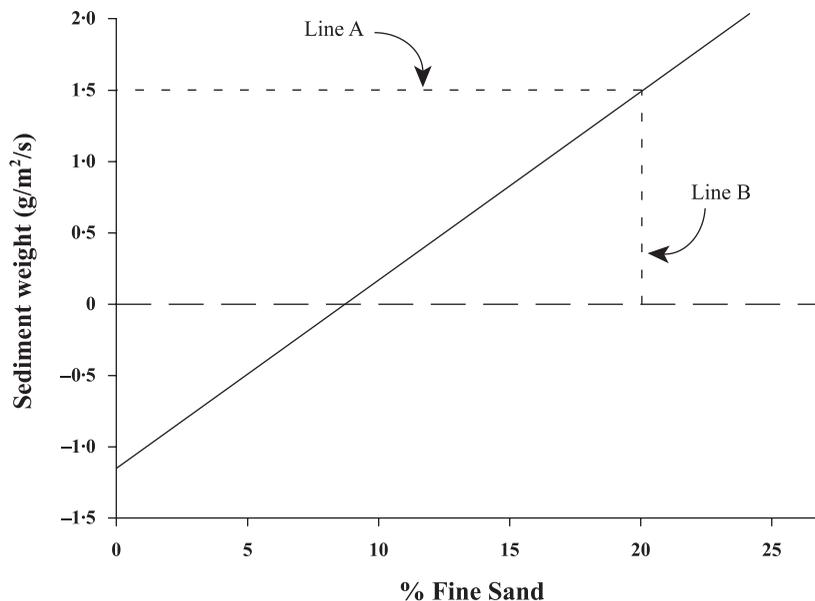


Figure 6. An illustration of how this study can be used to inform land management decisions in areas where biological soil crust development is low. To determine whether a soil-disturbing use is to be allowed at similar sites in the Mojave, the manager would need to know the soil texture at the site and the acceptable limits of soil loss. Using the regression results that best predict sediment yield from trampled sites (Table III), a manager can then draw a line (Line A) from the point of acceptable soil loss to meet the regression line. At the point where Line A intersects the regression line, a vertical line (Line B) is drawn down to the x-axis. The point at which Line B intersects the x-axis is the amount of fine sand that can be present before the acceptable level of soil loss is exceeded.

large differences in TFVs and sediment yield at the recently disturbed sites when compared to the control sites. This study also showed that new disturbance (via trampling in this case) had a greater effect at 'control' sites when compared to sites that had been recently disturbed. This finding contrasts with a study in southeastern Utah, USA, where disturbance applied to relatively well-developed crusts had less effect on TFVs than disturbance to crusts recovering from recent impact (Belnap and Gillette, 1997).

Land managers often need to decide whether to permit certain types of land use activities. In deserts, loss of soil stability, and the resultant loss of soil, is of concern. Therefore, ways to predict the susceptibility of soil surfaces to wind erosion are of value to managers. The results from this study indicate that at least 'ballpark' predictions are possible, as we obtained a linear relationship between sediment yield and site factors. Using the regression line of fine sand and sediment yield obtained by this study on trampled surfaces, a manager could set acceptable wind erosion limits and judge the vulnerability of a site accordingly, depending on the soil texture (Figure 6).

However, utilizing such an approach will require land managers to establish an upper limit on allowable soil loss over a given time period. Unfortunately, there is little information on what level might be appropriate. Eldridge and Leys (2003) suggest losses over 5 g soil/m² soil surface are to be avoided. This study and recent studies at both the plot (Belnap *et al.*, unpublished work) and landscape level (Chavez *et al.*, unpublished work) throughout the Mojave Desert show that most soil surfaces in this desert produce very little sediment unless they are disturbed, regardless of lithology, surface age, landscape position or sediment type (e.g. alluvial, aeolian). The exceptions are playa edges, sand dunes and lake basins that continue to receive sediment deposits (e.g. Owens Lake). Thus, most soil surface-disturbing activities in the Mojave Desert will accelerate soil losses above natural background levels. Dust input (Reheis, 2003) and rock weathering (Dregne, 1983) rates are currently very low. Therefore, soil formation rates are low as well. Thus, soil losses in desert regions should be considered irreplaceable within the time frame of most management plans and actions. All US land management agencies have a mandate to allow use while sustaining the potential of the land to recover from that use (e.g. National Park Service's Organic Act, Bureau of Land Management's National Environmental Protection Act). Given the vulnerability of Mojave Desert soils to wind erosion after soil surface disturbance and the soil-disturbing nature of most types of land use, maintaining this mandated balance will be difficult, if not impossible.

Conclusion

All previous studies, as well as this one, have demonstrated that biological soil crusts play a role in reducing soil loss by wind. However, the extent to which this occurs differs among deserts. In hot deserts, soil texture can play a dominant role in the susceptibility of a soil surface to wind erosion. This is in contrast to sites where higher precipitation allows higher biological crust biomass to develop and where this biomass is the main determinant of soil erosion rates.

When surfaces are newly disturbed, their vulnerability to wind erosion increases dramatically. The biological and physical crusts are crushed, soil aggregate structure is destroyed, and rocks are pushed below the surface. In this study, sites with recent (<3 years) previous disturbance were more vulnerable to wind erosion than those with a more distant (>20 years) disturbance history. Because current dust inputs are generally low in the Mojave Desert, accelerated soil losses due to surface disturbance are unlikely to be replaced in the near future.

Acknowledgements

We would like to especially thank Ruth Sparks at the Fort Irwin National Training Center, Department of Defense, who funded this project and made the necessary arrangements at Fort Irwin. Additional funding and support were provided by the USGS Mojave Priority Ecosystem Program. Tonya Troxler, Justin Van Zee, Scott Swarthout and Sasha Reed provided field assistance, with editorial assistance provided by Beth Roy and Tina Kister.

References

- Belnap J. 2003. Biological soil crusts and wind erosion. In *Biological Soil Crusts: Structure, Function, and Management*, Belnap J, Lange OL (eds). Springer-Verlag: Berlin; 339–347.
- Belnap J, Eldridge D. 2003. Disturbance and recovery of biological soil crusts. In *Biological Soil Crusts: Structure, Function, and Management*, Belnap J, Lange OL (eds). Springer-Verlag: Berlin; 363–383.
- Belnap J, Gardner JS. 1993. Soil microstructure in soils of the Colorado Plateau: the role of the cyanobacterium *Microcoleus vaginatus*. *Great Basin Naturalist* **53**: 40–47.

- Belnap J, Gillette DA. 1997. Disturbance of biological soil crusts: impacts on potential wind erodibility of sandy desert soils in southeastern Utah. *Land Degradation and Development* **8**: 355–362.
- Belnap J, Gillette DA. 1998. Vulnerability of desert biological soil crusts to wind erosion: the influences of crust development, soil texture, and disturbance. *Journal of Arid Environments* **39**: 133–142.
- Belnap J, Warren SD. 2002. Patton's tracks in the Mojave Desert, USA: an ecological legacy. *Arid Land Research and Management* **16**: 245–258. DOI: 10.1080/15324980290000377
- Belnap J, Büdel B, Lange OL. 2003. Biological soil crusts: characteristics and distribution. In *Biological Soil Crusts: Structure, Function, and Management*, Belnap J, Lange OL (eds). Springer-Verlag: Berlin; 3–30.
- Chartes CJ. 1992. Soil crusting in Australia. In *Soil Crusting: Chemical and Physical Processes*, Sumner ME, Stewart BA (eds). Lewis Publishers: Boca Raton, FL; 339–365.
- Danin A, Yaalon DH. 1982. Silt plus clay sedimentation and decalcification during plant succession in sands of the Mediterranean coastal plain of Israel. *Israel Journal of Earth-Sciences* **31**: 101–109.
- Danin A, Bar-Or Y, Dor I, Yisraeli T. 1989. The role of cyanobacteria in stabilization of sand dunes in southern Israel. *Ecologia Mediterranea* **XV**: 55–64.
- Dregne HE. 1983. *Desertification of Arid Lands*. Harwood Academic Publishers: New York.
- Dulieu D, Gaston A, Darley J. 1977. La dégradation des pâturages de la région N'Djamena (République du Tchad) en relation avec la présence de cyanophycées psammophiles – étude préliminaire. *Revue d'Elevage et de Médecine Vétérinaire des Pays Tropicaux*. **30**: 181–190.
- Eldridge DJ, Greene RSB. 1994. Microbiotic soil crusts: A review of their roles in soil and ecological processes in the rangelands of Australia. *Australian Journal of Soil Research* **32**: 389–415.
- Eldridge DJ, Leys JF. 2003. Exploring some relationships between biological soil crusts, soil aggregation and wind erosion. *Journal of Arid Environments* **53**: 457–466. DOI: 10.1006/jare.2002.1068
- Gee GW, Bauder JW. 1986. Particle-size analysis. In *Methods of Soil Analysis, Part 1*, Klute A (ed.). American Society of Agronomy: Madison, WI; 383–411.
- Gillette DA. 1978. Tests with a portable wind tunnel for determining wind erosion threshold velocities. *Atmospheric Environment* **12**: 2309–2313.
- Gillette DA, Adams J, Endo A, Smith D, Kihl R. 1980. Threshold velocities for input of soil particles into the air by desert soils. *Journal of Geophysical Research* **85**: 5621–5630.
- Goudie AS. 1978. Dust storms and their geomorphological implications. *Journal of Arid Environments* **1**: 291–310.
- Herrick JE, Whitford WG, de Soyza AG, Van Zee JW, Havstad KM, Seybold CA, Walton M. 2001. Field soil aggregate stability kit for soil quality and rangeland health evaluations. *Catena* **44**: 27–35.
- Kovda V. 1980. *Land Aridization and Drought Control*. Westview Press: Boulder, CO.
- Leys JF, Eldridge DJ. 1998. Influence of cryptogamic crust disturbance to wind erosion on sand and loam rangeland soils. *Earth Surface Processes and 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. *Journal of Geophysical Research* **102**: 23277–23287.
- Musick HB. 1998. Field monitoring of vegetation characteristics related to surface changes in the Yuma Desert, Arizona, and at the Jornada Experimental Range in the Chihuahuan Desert, New Mexico. In *Desert Winds: Monitoring Wind-Related Surface Processes in Arizona, New Mexico, and California*, Breed CS, Reheis MC (eds). US Geological Survey: Washington, DC; 71–84.
- Offer ZY, Goossens D, Shachak M. 1992. Aeolian deposition of nitrogen to sandy and loessial ecosystems in the Negev Desert. *Journal of Arid Environments* **23**: 355–363.
- Pluis JLA. 1994. Algal crust formation in the inland dune area, Laarder Wasmeer, the Netherlands. *Vegetatio* **113**: 41–51.
- Priestley CHB. 1959. *Turbulent Transfer in the Lower Atmosphere*. University of Chicago Press: Chicago, IL.
- Reheis M. 2003. *Dust deposition in Nevada, California, and Utah, 1984–2002*. Open-File Report 03-138. US Geological Survey: Denver, CO.
- Reynolds R, Belnap J, Reheis M, Mazza N. 1998. Eolian dust on the Colorado Plateau – magnetic and geochemical evidence from sediment in potholes and biologic soil crust. In *Proceedings: Dust Aerosols, Loess, Soils, and Global Change: An Interdisciplinary Conference and Field Tour on Dust in Ancient Environments and Contemporary Environmental Management*, Busacca A, Lilligren S, Newell K (eds). Washington State University, College of Agriculture and Home Economics: Seattle, WA; 231–234.
- Reynolds R, Belnap J, Reheis M, Lamothe P, Luiszer F. 2001. Aeolian dust in Colorado Plateau soils: nutrient inputs and recent change in source. *Proceedings of the National Academy of Sciences* **98**: 7123–7127.
- Ronen R, Galun M. 1984. Pigment extraction from lichens with dimethyl sulfoxide (DMSO) and estimation of chlorophyll degradation. *Environmental and Experimental Botany* **24**: 239–245.
- SPSS. 2003. *SPSS Version 12.0*. SPSS, Inc.: Chicago, IL.
- Tsoar H, Møller JT. 1986. The role of vegetation in the formation of linear sand dunes. In *Aeolian Geomorphology*, Nickling WG (ed.). Allen and Unwin: Boston, MA; 75–95.
- Tsoar H, Pye K. 1987. Dust transport and the question of desert loess formation. *Sedimentology* **34**: 139–153.
- Van den Ancker JAM, Jungerius PD, Mur LR. 1985. The role of algae in the stabilization of coastal dune blowouts. *Earth Surface Processes and Landforms* **10**: 189–192.
- Williams JD, Dobrowski JP, West NE, Gillette DA. 1995. Microphytic crust influence on wind erosion. *Transactions of the American Society of Aeronautical Engineers* **38**: 131–137.