

DISTURBANCE OF BIOLOGICAL SOIL CRUSTS: IMPACTS ON POTENTIAL WIND ERODIBILITY OF SANDY DESERT SOILS IN SOUTHEASTERN UTAH

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ABSTRACT

Friction threshold velocities (FTVs) were determined for biological soil crusts in different stages of recovery. Particles on the surface of crusts that had been relatively undisturbed for at least 20 years were found to have significantly higher FTVs than those that had been disturbed 5, 10 or 1 years previously (376, 87, and 46 cm sec⁻¹, respectively). FTV's for crust breakage was also much higher for undisturbed crusts when compared to the previously disturbed crusts (573, 148, and 88 cm sec⁻¹, respectively). All crusted surfaces were more stable than bare sand, which had an FTV of 16 cm sec⁻¹. Disturbance treatments were then applied to the three crustal classes. Disturbance significantly reduced the FTVs of all classes by 73–92 per cent. Comparing crustal FTVs with mean and high monthly wind speeds found in this region, it was observed that only crusts that had been undisturbed for approximately 20 years or more were able to protect soil surfaces from wind gusts expected on the average of once a month. Other crustal classes, as well as all disturbance treatments, had FTVs lower or equal to that of commonly occurring winds in this region. Because most of the crustal biomass occurs in the top 0–3 mm of soils, even slight soil loss can negatively influence stability and nutrient inputs to this ecosystem. © 1997 John Wiley & Sons, Ltd.

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INTRODUCTION

Biological soil crusts, also called 'cryptobiotic', 'microbiotic', 'microphytic' or 'cyanobacterial–lichen' soil crusts, are a dominant feature of most semiarid and arid landscapes throughout the world. These crusts differ in species composition and occur on a variety of soils. As a result, crustal function in different geographic regions might vary in regard to ecological processes such as rainfall infiltration and seedling establishment (Harper and Marble, 1989; Johansen, 1993; West, 1990). However, most studies agree that biological soil crusts reduce wind erodibility of soil surfaces (Leys, 1990; MacKenzie and Pearson, 1979; Williams, *et al.*, 1995), although one study found no significant differences (Andrew and Lange, 1986). Scanning electron microscope studies done by Belnap and Gardner (1993) show that the extracellular sheath material of cyanobacteria bind soil particles together, providing soil surface protection.

Biological soil crusts are highly susceptible to disturbance, especially in soils with low aggregate stability such as sands (Belnap and Gardner, 1993; Gillette, *et al.*, 1980; Webb and Wilshire, 1983). Cyanobacterial filaments, lichens and mosses are brittle when dry, and crush easily when subjected to compressional or shear forces by activities such as trampling or vehicular traffic. Because crustal organisms are only metabolically active when wet, re-establishment time is slow in arid systems. While cyanobacteria are mobile, and can often move up through disturbed sediments to reach light levels needed for photosynthesis, lichens and mosses are incapable of such movement and often die as a result. On newly disturbed surfaces, mosses and lichens often have extremely slow colonization and growth rates. Assuming adjoining soils are stable and rainfall is

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average, recovery rates for lichen cover in southern Utah has been most recently estimated at a minimum of 45 years, while recovery of moss cover was estimated at 250 years (Belnap, 1993). Due to this slow recolonization of soil surfaces by the different crustal components, crusts can be found in many stages of development.

Wind is a major erosive force in deserts where there is little organic matter or vegetation cover to protect soil surfaces. Soil deposition by wind often exceeds that of fluvial deposition in these drier regions (Goudie, 1978; Williams, *et al.*, 1995). Sediment production from soil surfaces depends on the force of wind needed to detach particles from soil surfaces (threshold friction velocity). Since wind erosion is of major concern both in the western USA and worldwide (Dregne, 1983), it is important to understand how soil surface disturbance affects threshold velocities.

While previous studies have addressed the role soil crusts play in stabilizing desert soil surfaces, none has examined how threshold velocities might vary between stages of crustal development or how disturbance might differentially influence various crustal types. The purpose of this study was to determine typical threshold velocities for different stages of biological soil crust development and to determine the effects of different soil surface disturbances on various stages of crustal development.

METHODS

The study site was located approximately 16 km south of Moab, Utah, USA, in Rizzo sandy loam soils. The dominant vegetation type is pinyon and juniper at an elevation of 1400 m. Annual precipitation is 250 mm, with 30 per cent of the rainfall occurring as late summer monsoons. Treatments were applied and measurements taken in July 1995 when soils were dry. All areas tested were located within a 300 m circle, with the same substrate type, soil depth and slope.

Soils were collected and analyzed for sand, silt and clay content. Biological soil crust development was placed in one of four time categories, based on previous experiments regarding recovery rates after disturbance from four-wheel vehicles or foot traffic (Belnap, 1993, unpublished data). These included:

- (a) Class 0: bare sand, with no visible biological crustal development, indicating very recent disturbance from vehicle or foot traffic.
- (b) Class 1: flat crusts, with no visible frost heaving or lichen cover and low cyanobacterial biomass, indicating disturbance from vehicles or foot traffic within one year of observation.
- (c) Class 2: moderately bumpy biological crusts with no lichen or moss development and moderate cyanobacterial biomass levels, indicating vehicular or foot traffic disturbances 5–10 years prior to observation.
- (d) Class 3: biological crusts were very bumpy, with full lichen and moss development and high cyanobacterial biomass, indicating no vehicular or foot traffic disturbance for at least 20 years.

Friction threshold velocities for movement of loose sand particles on the undisturbed surface (CON in Figure 2), and surface integrity of the crusts (SI in Figure 3) were determined for each crust type at two replicated sites. The FTV for particle movement was defined as the friction velocity at which surface particles were both detached from the soil surface and carried away by the generated wind. The FTV for surface integrity was the friction velocity at which large, intact chunks of the surface were detached and blown away. Because wind stress equals the square of friction velocity times the density of air, relative resistances of the different crustal classes to wind erosion are defined and reported as the square of the ratio of threshold friction velocities between the classes being compared.

Once FTVs were determined for the different undisturbed crustal classes, disturbance treatments were applied to each crust class at each site. These treatments included:

- (1) Treatment F1: one pass by walking on crusts with lug-soled boots.
- (2) Treatment V1: one pass of a four-wheel drive vehicle with knobbed tires.
- (3) Treatment V2: two passes of a four-wheel drive vehicle with knobbed tires.



Figure 1. Portable wind tunnel, assembled in the field.

Comparisons across the three crustal classes were done using a two-way ANOVA and multiple range test. *T*-tests were used to distinguish between disturbance treatments and controls.

Wind Tunnel

A portable, open-bottomed wind tunnel, 150 mm × 150 mm cross-section by 2.4 m length was used so that many wind speeds could be formed over the desert surface (Figure 1: 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 collected at several heights above the surface midway across the end of the working section. The Pilot tube anemometer was calibrated and corrected for temperature and pressure changes.

To obtain FTVs for the undisturbed control crusts, wind speed in the tunnel was gradually increased until consistent forward sand particle movement was observable across the soil surface. Measurements of airflow velocities were then recorded at the soil surface and 3.2, 6.4, 12.7, 25.4, 38.1, 50.8, 63.5, 76.2, 88.9, 101.6 mm above the soil surface, yielding wind profiles for the controls. To obtain wind profiles for surface integrity values, wind speeds were then increased until chunks of the surface crusts detached. For areas receiving foot or vehicle treatments, FTVs were determined for the undisturbed surface, after which the tunnel was removed and treatments applied. After treatment, the tunnel was replaced and then the same area remeasured. Data for the mean horizontal wind velocity U (cm sec⁻¹) versus height z (mm; wind profile data) were fitted to the function for aerodynamically rough flow (Priestley, 1959), using a linear least squares routine:

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

where U_{*t} is friction velocity, kz is roughness height characteristic of the surface, U_i is wind speed at the particle movement threshold, and k is Von Karman's constant. Threshold velocities and aerodynamic roughness heights are reported in terms of friction velocity and roughness height. A total of 196 wind profiles were obtained for this study.

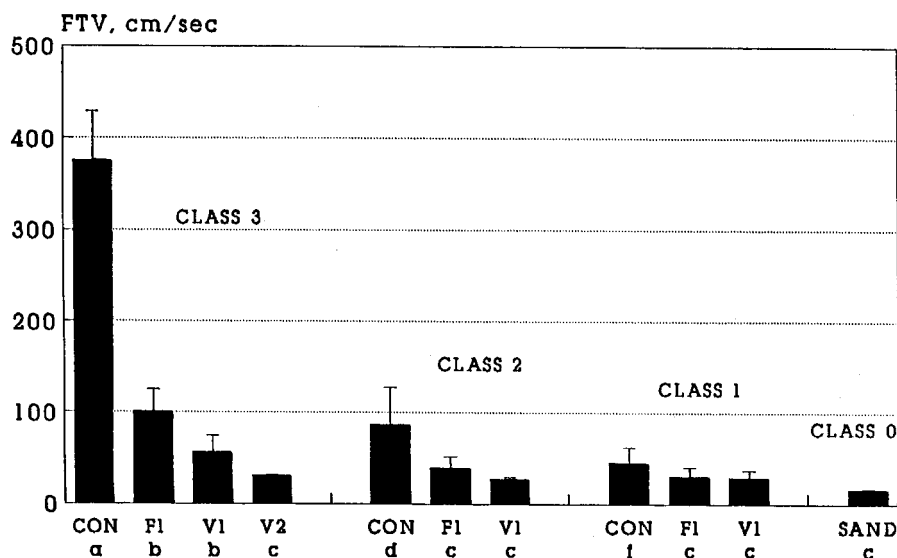
Mean, median and maximum wind speeds recorded in this region were converted to rough estimates of friction velocity. This was done using a drag coefficient for 2 m winds of 0.01 which corresponds to a surface roughly similar to the test site. Using similar surfaces as those described by Priestley (1959), the aerodynamic roughness height of this surface was estimated to be 3.7 cm. The conversion factor for wind speeds in meters per second to friction velocities in centimeters per second is 10.

RESULTS

Characteristics of soils found at the sites are listed in Table I. Friction threshold velocities for soil particle movement in crustal class controls and treatments are presented in Figure 2. Undisturbed class 3 crusts had FTVs of 376 cm sec^{-1} compared to 16 cm sec^{-1} for bare sand; consequently, class 3 crusts had 552 times the wind resistance of bare sand. Undisturbed class 1 crusts had average FTVs of 46 cm sec^{-1} , indicating

Table I. Means and standard error for soil texture of different crust types. No statistically significant differences were found between sand, silt or clay content of the three soils ($p > 0.05$)

Crust class: Age	Sand	Silt	Clay
C1: 1 year	76 + / - 4.9	13 + / - 4.3	11 + / - 0.8
C2: 5 year	66 + / - 2.0	20 + / - 0.5	14 + / - 1.5
C3: >10 year	65 + / - 4.4	21 + / - 4.2	14 + / - 0.9



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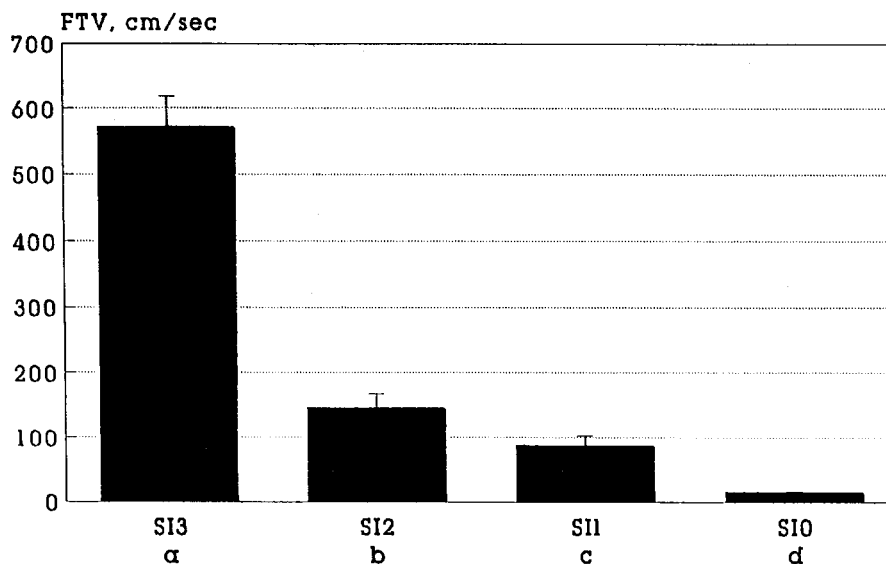
Figure 2. FTVs for individual soil particle detachment in different crustal classes before and after disturbance treatments. CON = control crust; F1 = one pass with lugged boot; V1 = one pass with vehicle; V2 = two passes with vehicle. Within each crustal class, all treatment values were significantly lower than control surfaces of the same class. Within each class, no treatments differed significantly from each other, with the exception of class 3 (V2 was different from F1 and V1). All crustal class controls differed from each other. Categories with different lower case letters differ significantly from each other ($p < 0.05$). Error bars indicate standard error.

that class 3 crusts have 64 times the wind resistance of class 1 crusts. Class 3 crusts showed 19 times the wind resistance of class 2 crusts, whose average FTV was 87 cm sec^{-1} . Figure 3 presents the FTVs required to break up the surface integrity of the soil surface. Maximal wind tunnel velocity possible (573 cm sec^{-1}) did not break the surface integrity of class 3 crusts; consequently, our maximum FTV underestimates the true FTV for this crust class. Breakage of the surface crust was seen at FTVs of 88 cm sec^{-1} for class 1 crusts and 148 cm sec^{-1} for class 2 crusts. Therefore, class 3 crusts showed more than 15–42 times greater wind resistance than lesser-developed crusts, while class 2 crusts had 2.6 times greater wind resistance than class 1 crusts. All crustal classes had significantly higher resistance than that of bare sand, which had an FTV of 16 cm sec^{-1} . Class 3 crusts showed more than 1283 times the wind resistance than that of bare sand, while class 2 and class 1 crusts showed 81 and 30 times, respectively, the wind resistance than that of bare sand.

All applied disturbances significantly decreased FTV in all crust classes when compared to the controls for each crustal class. However, disturbance affected the well-developed class 3 crusts the least. Treatment F1 (one pass of footprints) reduced class 3 crusts' FTV by 73 per cent; however, this was still well above the FTVs of undisturbed class 2 and class 1 crusts. On class 3 crusts, treatment V1 (one vehicle pass) reduced FTV by 85 per cent, a value just below that for undisturbed class 2 crusts. It took treatment V2 (two vehicle passes) on class 3 crust to reduce the FTV to values comparable to that for all disturbances to other crust classes (a 92 per cent reduction), and to approach values for bare sand. In comparison, class 1 and 2 crusts showed very little resistance to disturbance, with treatments 1 and 2 resulting in FTVs equivalent to bare sand. The sum of the squares for all ANOVA consistently showed a greater difference between crustal classes than between any treatments.

DISCUSSION

This study demonstrated that the degree of organic soil crust development can be very important in determining FTVs of soil surface. Mean, median and maximum wind speeds for 1989–91 (30 minute averages) at a site in the same region are presented in Table II (as reported by Williams, *et al.*, 1995). Table III shows



7/95; all diff at $p(0.01)$

Figure 3. FTVs required to break up surface integrity (SI) of soils (detachment and loss of large chunks of untreated crustal classes). SI3 = class 3 crust; SI2 = class 2 crust; SI1 = class 1 crust; SI0 = class 0 crust. All values were significantly different ($p < 0.01$). Error bars indicate standard error.

Table II. Mean, median and maximum (m sec^{-1} ; averaged over 30 minutes) wind speeds and friction velocity estimates recorded for a research site in the region, 1989–91 (as reported in Williams, *et al.*, 1995)

Year	Mean	Median	Maximum	FTV estimate
1989	1.11	0.58	14.81 (June)*	148
1990	0.97	0.50	13.42 (July)*	134
1991	1.03	0.53	13.67 (March)*	137

*Month when maximum wind speed was recorded.

Table III. Maximum wind speeds (m sec^{-1}) and friction velocity estimates reported for the Moab area, 1982–88 (as reported in Williams, *et al.*, 1995)

Month	Wind speed	Friction velocity	Month	Wind speed	Friction velocity
Jan.	33	330	July	32	320
Feb.	29	290	Aug.	27	270
Mar.	35	350	Sept.	34	340
Apr.	32	320	Oct.	28	280
May	35	350	Nov.	32	320
June	32	320	Dec.	28	280

maximum monthly winds in Moab, Utah, 10 miles north of the research site. Conversion of these wind speeds to rough estimates of friction velocity showed that mean, medium and maximum winds from both sites in this region never exceeded the FTV for undisturbed class 3 crusts. In contrast, FTVs for class 0, 1, and 2 crusts were all below monthly maximum wind speed at both sites. Consequently, in the absence of other protecting elements like vegetation, only relatively undisturbed soil crusts would be capable of protecting soil surfaces from winds that commonly occur in this region. Even after five to ten years recovery, crustal = integrity of class 1 and 2 crusts is still not adequate to protect soil surfaces from monthly maximum wind speeds.

This study also showed that previously disturbed soils had less resistance to additional disturbance than the relatively undisturbed soils, while all soil surface disturbances had negative impacts on the FTVs of all crust classes. Though foot traffic in the class 3 crusts resulted in an FTV still above mean wind speeds of the region, it reduced the ability of this crust to resist monthly maximum winds. Any vehicular disturbance significantly reduced the ability of these surfaces to resist wind erosion by reducing FTVs below average monthly wind speeds. All disturbed crusts were at risk from the monthly high wind speeds reported from this area. In addition, adjoining areas are placed at risk of being 'sand-blasted' by material from disturbed areas, and thus a small disturbance might trigger much larger impacts.

Friction threshold velocities reported in this study are similar to values reported in other work. Selah and Fryrear (1995) reported an FTV of 31 cm sec^{-1} for dry bare soils, compared to 16 cm sec^{-1} in this study. Gillette (1988) reported an FTV of 290 cm sec^{-1} in rain-crustured soils in the Mojave, and $20\text{--}60 \text{ cm sec}^{-1}$ for loose sandy soils (Gillette, *et al.*, 1980). Gillette, *et al.* (1980) also showed that FTV increases with increasing clay and silt in soils. This is supported by the work of Williams, *et al.* (1995). They reported FTVs of 200 cm sec^{-1} for alluvial soils with fairly high silt–clay contents that had been fenced off from grazing disturbance for three years. As would be expected for a more recently disturbed crust, these soils had a much lower lichen cover than those in the current study (2 vs. 20 per cent cover), and would be considered class 2 crusts. As suggested by the work of Gillette, *et al.* (1980), the silty soils in the study by Williams, *et al.* (1995) showed higher FTVs than the class 2 sandy soil crusts examined in this study, and lower FTVs than the sandy class 3 crusts.

Decreasing FTVs are directly associated with increased sediment movement (Leys, 1990; Williams, *et al.*, 1995). Increased sediment movement can result in many direct and indirect problems. Slow recovery rates

recorded for crusts in this region (Belnap, 1993) would result in disturbed soils being exposed to erosion for from 50 to 250 years after disturbance. Soil formation is estimated to take 5000 to 10 000 years (Webb and Wilshire, 1983); therefore, soil loss can have long-term consequences. Work done by Garcia-Pichel and Belnap (1996) has demonstrated that over 75 per cent of the photosynthetic biomass, and almost all photosynthetic productivity is from organisms in the top 0.3 mm of these soils. Therefore, very small soil losses, or burial of photosynthetic organisms by wind or water-borne sediments, can dramatically reduce site fertility. In addition, many plants have relatively inflexible rooting depths, and often cannot adapt to rapidly changing soil depths.

CONCLUSIONS

This study demonstrated that disturbance to biological soil crusts on sandy soils in southeastern Utah has left soil surfaces susceptible to wind erosion from commonly occurring wind speeds for at least twenty years. In addition, previously disturbed soil crusts were shown to be less resistant to new disturbances than previously undisturbed soil crusts.

Soil erosion in arid lands is a major threat worldwide. Beasley, *et al.* (1984) estimated that in rangeland of the USA alone, 3.6 million hectare has some degree of accelerated wind erosion. Relatively undisturbed biological soil crusts can contribute a great deal of stability to otherwise highly erodible soils. Unlike vascular plant cover, crustal cover is not reduced in drought, and unlike rain crusts, these organic crusts are present year-round. Consequently, they offer stability over time and in adverse conditions that is often lacking in other soil surface protectors. Unfortunately, the more-disturbed class 0, 1 and 2 crusts now cover vast areas in the western USA as a result of the ever-increasing recreational and commercial uses of these semiarid and arid areas. Based on the results of this study, the tremendous land area currently being impacted may lead to significant increases in regional and global wind erosion rates. For these reasons, management policies of arid and semiarid regions should reflect the important role these crusts play in soil surface stability, and should reduce disturbance to these biological crusts whenever possible.

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REFERENCES

- Andrew, M. H. and Lange, R. T. 1986. 'Development of a new piosphere in arid chenopod shrubland grazed by sheep. 2. Changes in the vegetation', *Australian Journal of Ecology*, **11**, 411–424.
- Beasley, R. P., Gregory, M. and McCarty, T. R. 1984. *Erosion and Sediment Pollution Control*, 2nd edn., Iowa State University Press, Dubuque.
- Belnap, J. 1993. 'Recovery rates of cryptobiotic soil crusts: assessment of artificial inoculant and methods of evaluation', *Great Basin Naturalist*, **53**, 89–95.
- Belnap, J. and Gardner, J. S. 1993. 'Soil microstructure of the Colorado Plateau: the role of the cyanobacterium *Microcoleus vaginatus*', *Great Basin Naturalist*, **53**, 40–47.
- Dregne, H. E. 1983. *Desertification of Arid Lands*, Harwood Academic Publishers, New York.
- Garcia-Pichel, F. and Belnap, J. 1996. 'The microenvironments and microscale productivity of cyanobacterial desert crusts', *Journal of Phycology*, **32**, 774–782.
- Gillette, D. A. 1978. 'A wind tunnel simulation of the erosion of soil: effect of soil texture, sandblasting, wind speed, and soil consolidation on dust production', *Atmospheric Environments*, **12**, 1735–1743.
- Gillette, D. A. 1988. 'Threshold friction velocities for dust production for agricultural soils', *Journal of Geophysical Research*, **93**, 645–662.
- Gillette, D. A., Adams, J., Endo, A., Smith, D. and Kihl, R. 1980. 'Threshold velocities for input of soil particles into the air by desert soils', *Journal of Geophysical Research*, **85**, 5621–5630.
- Goudie, A. S. 1978. 'Dust storms and their geomorphological implications', *Journal of Arid Environments*, **1**, 291–310.

- Harper, K. T. and Marble, J. R. 1989. A role for nonvascular plants in management of arid and semiarid rangeland, pp. 135–169 in P. T. Tueller (ed.) *Vegetation Science Application for Rangeland Analysis and Management*, Kluwer Academic Publishers, Dordrecht.
- Johansen, J. R. 1993. 'Cryptogamic crusts of semiarid and arid lands of North America', *Journal of Phycology*, **29**, 140–147.
- Leys, J. N. 1990. *Soil crusts: their effect on wind erosion*, Research Note 1/90, Soil Conservation Service of New South Wales, Australia.
- MacKenzie, H. J. and Pearson, H. W. 1979. 'Preliminary studies on the potential use of algae in the stabilization of sand wastes and wind blow situations', *British Journal of Phycology*, **14**, 126.
- Priestley, C. H. B. 1959. *Turbulent Transfer in the Lower Atmosphere*, University of Chicago Press, Chicago.
- Selah, A. and Fryrear, D. W. 1995. 'Threshold wind velocities of wet soils as affected by wind blown sand', *Soil Sciences*, **160**, 304–309.
- Webb, R. H. and Wilshire, H. G. (eds.) 1983. *Environmental Effects of Off-road Vehicles: Impacts and Management in Arid Regions*, Springer-Verlag, New York.
- West, N. E. 1990. 'Structure and function of soil microphytic crusts in wildland ecosystems of arid and semi-arid regions', *Advances in Ecological Research*, **20**, 179–223.
- Williams, J. D., Dobrowolski, J. P., West, N. E. and Gillette, D. A. 1995. 'Microphytic crust influences on wind erosion', *Transactions of the American Society of Agricultural Engineers*, **38**, 131–137.
- Wilshire, H. G. 1983. The impact of vehicles on desert soil stabilizers, pp. 31–51 in R. H. Webb and H. G. Wilshire (eds.) *Environmental Effects of Off-Road Vehicles: Impacts and Management in Arid Regions*, Springer-Verlag, New York.