LAND DEGRADATION & REHABILITATION, VOL. 2, 77-85 (1990)

FIELD MEASUREMENT OF THE SHELTERING EFFECT OF VEGETATION ON ERODIBLE LAND SURFACES

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ABSTRACT

Natural vegetation on erodible land surfaces, such as the loose sandy soils found in the southwestern United States and in Soviet Central Asia, absorbs part of the wind momentum flux (stress) and thus protects the erodible soil to a degree that depends on the geometry of plant distribution and profile. The sheltering effect of natural plants may be expressed as the ratio, R, of threshold friction velocity for the bare soil (determined in the laboratory or in specially prepared areas of bare soil in the field) to that for the naturally vegetated surface. We used new automated instrumentation to detect erosion thresholds in locations where erosion events are widely separated in time. Measured values of R were low for our most vegetated sites and nearer unity for the sparsely vegetated site.

KEY WORDS Desertification Vegetation Wind erosion Thresholds Degradation Southwestern USA Soviet Central Asia

INTRODUCTION

Land degradation by wind and reduction of the natural vegetation cover are often associated in semiarid lands. Vegetation reduction results in the lowering of the threshold friction velocity for wind erosion. Threshold friction velocity for wind erosion is that friction velocity just at the initiation of soil movement by the wind. The importance of the lowering of wind erosion thresholds by reduction of vegetation is most apparent in those marginal lands whose plant cover would be further depleted if the climate deteriorated slightly as a result of global climate change. Our concern is primarily with those lands where thresholds for land degradation are not far from the existing conditions.

To understand the threshold at which land degradation from wind erosion occurs on reduction of natural vegetation, it is necessary to understand the physical basis of the sheltering effect of vegetation. The physical basis is found in Marshall's (1971) classical study of the aerodynamics of surfaces having a variety of roughness shapes. Marshall developed equations for partitioning of wind momentum to the ground surface (floor) and to various roughness elements (for our application, plants) located in regular or random arrays on the floor, following the work of Kutzbach (1961), Hoerner (1965), and Schlichting (1936). His analysis of momentum partitioning forms the framework for our studies on vegetation sheltering of erodible soil from wind erosion.

This paper provides details on field and laboratory measurements necessary to evaluate partitioning of momentum by natural vegetation. It also reports our measurements expressing the sheltering effect of plants at three sites.

Editors' Note: This, and the companion paper which follows, offer a method to characterize the sheltering effect of vegetation (which helps to reduce land degradation through wind erosion).

0898-5812/90/020077-09$05.00

Received 17 September 1990
Accepted 12 December 1990

EXPERIMENTAL DETAILS

Theoretical Background

For our application, the important parameter in Marshall's (1971) analysis that expresses shear stress partitioning may be related to R, the ratio of threshold friction velocity for bare soil to that for vegetated soil. The analysis assumes an area having bare erodible soil with plants (non-erodible roughness elements) distributed over the surface. Shear stress partitioning was expressed following Schlichting (1936) as:

$$W = W_r + W_g, \tag{1}$$

where W is the overall force imparted to a roughened surface by a fluid passing over it, W_r is the force exerted on the roughness elements (plants), and W_g is the force exerted on the bare erodible soil. F is total floor area and F' total floor area of the bare soil. Inserting F:

$$W/F = W_r/F + (W_g/F')(F'/F) \tag{2}$$

which can be restated as:

$$\tau = W_r F + \tau_g(F'/F). \tag{3}$$

Where τ is total wind stress and τ_g is wind stress felt by the erodible particles.

At threshold of movement for erodible particles:

$$\tau_g = \sigma u_{*t}^2; \quad \text{and} \quad \tau = \sigma u_{*l}^2 \tag{4}$$

where u_* is the friction velocity (Priestley, 1959) and σ is air density. Threshold u_* measured without plants on the surface allows calculation of surface stress $\tau_g = \sigma\ u_{*t}$. Threshold u_* measured with plants on the surface may be expressed as:

$$\tau = W_r/F + \tau_g(F'/F) = \sigma u_{*l}^2 \tag{5}$$

The fraction of momentum flux going to the erodible surface (shear stress partitioning) is:

$$1 - \{W_r/[F\tau]\} = (\tau_g/\tau)(F'/F) \tag{6}$$

Rewriting, using the above definition of $R = u_{*t}/u_{*l}$ gives:

$$1 - \{W_r/[F\tau]\} = R^2(F'/F) \tag{7}$$

The two parameters expressing the stress partitioning in Equation 7 are R (ratio of threshold friction velocity without vegetation to threshold friction velocity with vegetation) and F'/F (a geometric factor describing the fraction of area covered by erodible soil). Our method of measuring R follows. This includes two methods to measure the threshold friction velocity for the erodible soil and one automated field method to measure the vegetated friction velocity. To measure the ratio F'/F, an objective scheme is reported by Musick and Gillette (see pp 87–94, this issue).

Detection of threshold for the erodible soil

Threshold velocities for two of our three test sites (described later) for loose, erodible soil (u_{*t}) were obtained as described by Gillette and Stockton (1989). In this method, a layer of a loose soil collected from the test site was laid on the floor of a laboratory wind tunnel in Boulder, Colorado. The tunnel is a modification of the tunnel used by Gillette and Stockton (1986) for studies of particle mass, momentum, and kinetic energy fluxes. The tunnel is configured as a straight, suction-type tunnel in which source air is first drawn through a honeycomb straightener, then through a 5:1 contraction section, to the working section, which is 15·5 cm wide and 19·5 cm high. Following the working section, a diffuser section leads to a high-speed fan with speed controls. The working section floor was covered with an approximately 1·0-cm-deep layer of soil particles.

Tests made of the flow showed a uniform laminar flow at the leading edge of the deposit in the working section and a turbulent boundary layer thickness of 10·0 ± 2·0 cm at a distance of 150 cm downwind of the leading edge of the deposit in the working section. The turbulent boundary flow was laterally uniform to within about 1·0 cm of the side walls of the tunnel. Flow was measured by a rake of six Pitot-static anemometers placed at 1·0 cm intervals, starting 1·0 cm above the deposit surface.

With the erodible soil in place, wind velocities were slowly increased in the tunnel; the threshold velocity profile was obtained when continuous movement of soil particles was first visible. Data for the mean velocity U *versus* height (wind profile data) were fitted to the function for aerodynamically rough flow (see Priestley, 1959):

$$U = (u_*/k)\ln(z/z_0) \tag{8}$$

where u_* is friction velocity, z is height above the surface, z_0 is roughness height characteristic of the surface, and k is von Karman's Constant.

For the Soviet Central Asian site (Shaartuz) the threshold velocity for un-vegetated loose soil on the surface was obtained *in situ*. A straight, cleared lane about 50 m long leading to our sampling equipment was aligned with the wind direction and threshold friction velocity was reached and surpassed. We obtained the wind data for this time and calculated the friction velocity for the unvegetated soil using Equation 8.

Detection of threshold friction velocity in the presence of natural vegetation

Threshold velocities for soils sheltered by natural vegetation in place at the test sites were obtained using the wind speed measurements from instruments on an automated 'Geomet' station (McCauley, *et al.*, 1984) for Yuma and Jornada, and a similar instrumented station at Shaartuz. Soil erosion measurements from a 'Sensit'* erosion detector were taken for all three sites. The instrumentation includes anemometry at three logarithmic levels above the mean maximum height of the vegetation at the test sites. The exact heights differed slightly for the three sites, but the approximate anemometer heights were 1·0, 3·0, and 6·0 m. Mean wind speeds at each of these heights were calculated every six minutes using the solar-powered, satellite-relay data collection and transmission system for the Geomet stations at Yuma and Jornada. For the Asian site (Shaartuz) we used a data logger to record the data and used a two-minute averaging time. Because the wind profile for strong winds possesses a virtually linear increase of mean wind speed with logarithm of exact height above the displacement height, a value for u_* could be calculated for each half hour at Shaartuz and for six minute intervals at the other sites, using the equation:

$$u(z)/u_* = 2{\cdot}5\ \ln[(z - d)/z_0] \tag{9}$$

Where z_0 is aerodynamic roughness height, and d is displacement height.

Wind erosion was detected by the 'Sensit' erodible mass monitor. This sensor provides a response to impacting particles that strike its active area, a lead titanate zirconate. The active area is a ring-shaped, coated, piezoelectric crystal mounted on a 2·5-cm-diameter stainless-steel post that protrudes 10·0 cm (20·0 cm at Jornada) above the ground surface. The ring mounted on a vertical post makes the sensor independent of wind direction. Figure 1 shows the configuration of the piezoelectric ring and the sensor mounting post.

The signal provided by the 'Sensit' is the output from piezoelectric response to particle impacts. Background electrostatic noise, and piezoelectric response to background wind vibration have been electronically removed. Circuitry was designed to provide an integrator of instrumental response that clearly distinguishes electronic noise from particle impact signal and subtracts that noise from the output. Electrostatic noise caused by the discharge of charged particles is eliminated by a special high-dielectric coating on the sensor's outer surface. The density of this outer coating has been closely matched to the density of the crystal to provide optimum kinetic energy transfer to the crystal.

The crystal is suspended by soft, molded, synthetic rubber supports. The mechanical dampening of this material was selected to acoustically insulate the sensor from vibrations generated by particles striking its

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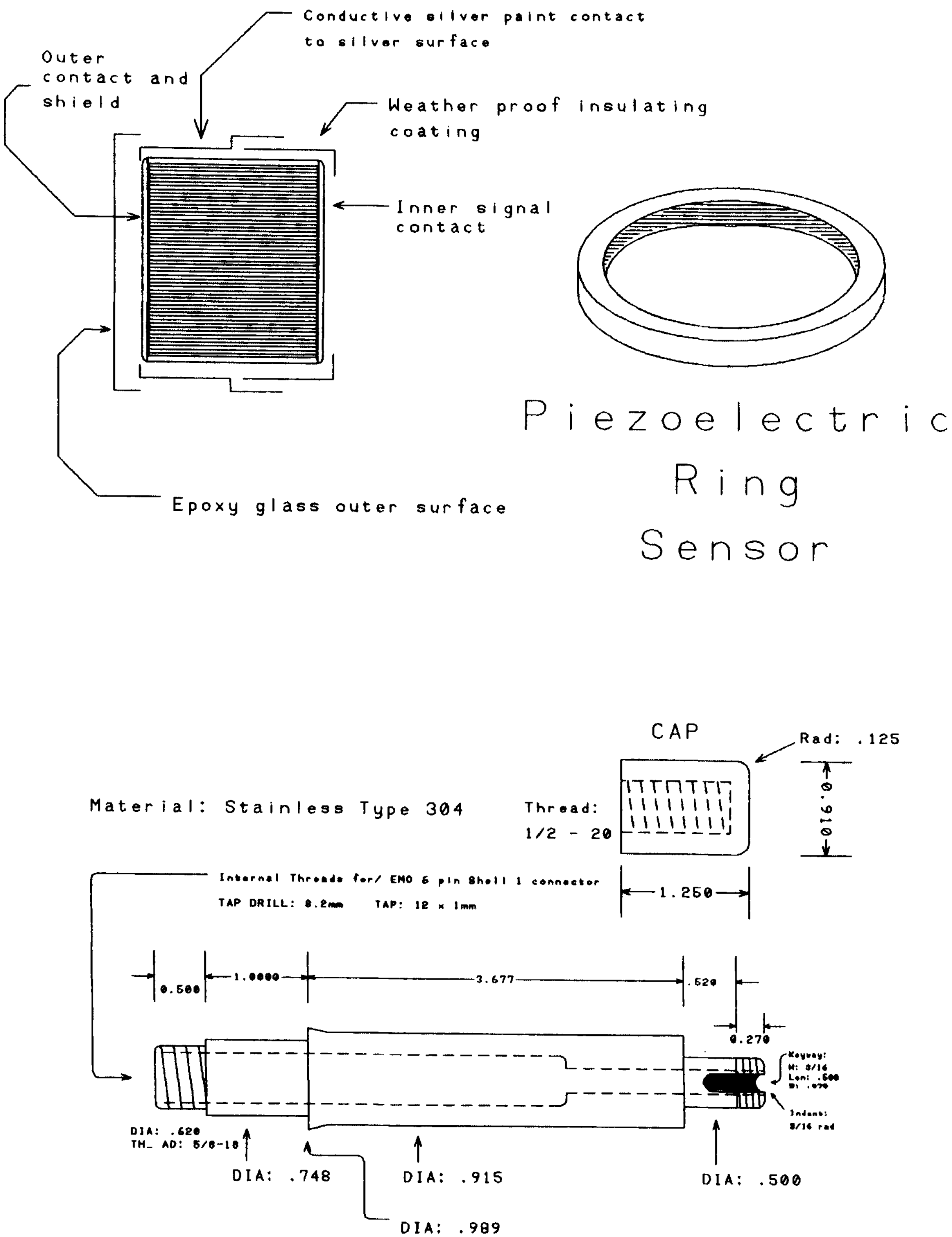

Figure 1. Schematic diagram of the 'Sensit' eroding mass monitor

mounting structure. The rubber supports and the protective outer coating of the sensor's surface provide a weather-proof seal. The structure that supports the sensor (see Figure 1) is stainless-steel which is resistant to corrosion and abrasion, making is suitable for use in hostile environments. The post is mounted atop a sealed, waterproof, and insulated cylindrical electronics housing buried in the ground; only the vertical post support for the piezoelectric ring is above ground.

Because of its large dynamic range, the 'Sensit' is sensitive to the threshold of wind erosion; the signal that follows the initiation of soil saltation (a hopping motion typical of sand-sized particles moved by wind), is clearly detected. In field tests at Big Spring, Texas, the 'Sensit' showed agreement with measurements taken by a continuously weighing collector of the time of onset of erosion (the time of threshold).

We used the 'Sensit' instrument in this experiment to detect the onset of saltation. This approach was necessary for vegetated surfaces, where episodes of wind erosion are widely and sporadically spaced in time. For example, our Jornada site had only one occurrence of wind erosion in the first year of operation. Such conditions make an automated monitoring system necessary. 'Sensit' data were collected at the same rate as average wind speeds.

Field locations for the experiment

Two of the three test sites for measurements of momentum partitioning between vegetation and erodible soils are part of the US Geological Survey Desert Winds network (McCauley, *et al.*, 1984). These sites are located on the Jornada del Muerto Plain north of Las Cruces, New Mexico and in the Sonora Desert near Yuma, Arizona. These instrumented Geomet sites were set up in the 1980s to provide data for monitoring desertification and greenhouse effect-induced climate warming impacts on marginal lands. A third test site is the site of joint US/USSR Desert Dust experimental site in the Shaartuz District of the Tadzhik SSR (Tadzhikistan), about 40 km from the Afghanistan border.

Jornada del Muerto. The Jornada del Muerto is a semiarid area with low relative humidity, high solar radiation, and highly variable precipitation averaging less than 250 mm per year. Detailed information on the local geology and soil morphology can be found in the US Department of Agriculture (USDA) Desert Soil-Geomorphology Project (Gile, *et al.*, 1981) and in other reports by the USDA, which operates the Jornada Experimental Range there. High winds are frequent at the site, especially during the dry spring season when vegetative cover as at its minimum. Much of the area has undergone a dramatic change in vegetation, from desert grassland to shrubland, within the last century (Buffington and Herbel, 1965); marked changes occurred as recently as the drought of 1951–1956 (Herbel, *et al.*, 1972; Wright, 1982; Hennessy, *et al.*, 1983). On sandy soils, the change from grassland to shrubland has been accompanied by the formation of coppice dunes (dunes held in place by vegetation) around the shrubs. Vegetative cover is sparse on the dune flanks and inter-dune areas, the long-term measurements of soil movement have shown that '... mesquite duneland, while having an appearance of stability, are actually a dynamic, constantly shifting system ....' (Gibbens, *et al.*, 1983).

Eolian modifications of soil properties have exacerbated the change from grassland to shrubland in drought years and hindered grassland recovery in subsequent wetter years (Wright, 1982; Hennessy, *et al.*, 1983). The influence of eolian processes over long time intervals is evident in large-scale imagery of the Jornada area. The site of the Desert Winds Geomet station (see Figure 2) is on the ecotone (the boundary between grassland and shrubland). If irreversible processes leading to desertification are taking place, this site will become more like the shrubland.

Yuma. The Yuma Geomet site (see Figure 3) is in a low basin in the broad lower valley of the Colorado River. It is at the upwind end of the largest active erg (sand sea) in North America (Breed, *et al.*, 1984), which extends southward across the USA border into northern Sonora, Mexico. The site is an arid area surfaced with alluvium from the Gila Mountains which has been reworked by wind into thick sand sheets and dunes. This eolian veneer, which extends to adjacent highlands, absorbs the generally light (less than 100 mm per year) and highly variable convective rainfall, preventing runoff from the adjacent highlands except in highly unusual flood events. Vegetation at the site normally consists of extremely sparse shrubs with very little grass, but substantial variability in the extent of the vegetative cover has been observed since 1981 at this site (MacKinnon, *et al.*, 1990).

Figure 2. Jornada del Muerto test site near Las Cruces, New Mexico

Figure 3. Yuma, AZ Geomet test site. (Photograph by C. S. Breed, US Geological Survey)

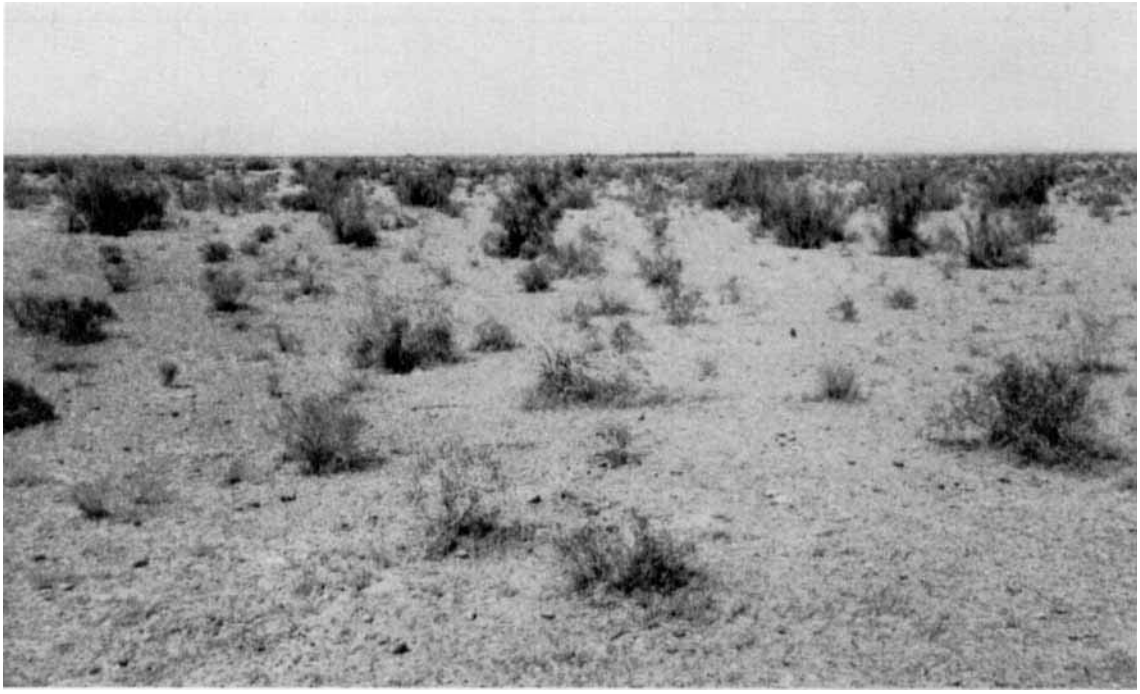

Figure 4. Shaartuz Tadzhikistan test site

Shaartuz. The Shaartuz region of Tadzhikistan is southwest of the city of Dushanbe and north of the Amu Darya River which forms the border of the USSR with Afghanistan. The test site is about 15 km north of the Amu Darya River in the center of the Kafirnigan River Valley. The probability of rainfall at the test site is less than one day in the 92 days from 1 June to 1 September. Annual rainfall is less than 200 mm. The soil at the location is loessial, and the frequency of dust storms at the location is 10 to 30 per year. The desert region of Afghanistan is the primary source for large-scale dust storms that transport dust northward across this site. Vegetation is quite sparse at this site and represents the least vegetation cover for the three sites we are considering. Figure 4 shows the Shaartuz site where the instrumentation was set up.

RESULTS

Computed friction velocity and 'Sensit' response are plotted in Figure 5 against time for a dust storm at the Jornada site on 21 April, 1988. Isolated response is seen occasionally in the 'Sensit' time-series, but a consistent pattern of movement is not seen until after 800 minutes. After that time, wind speed greater than about 110 cm s^{-1} is accompanied by increasing 'Sensit' response. Because threshold velocity is the minimum velocity above which consistent movement of soil occurs, the bursts of 'Sensit' response for friction velocity less than 110 cm s^{-1} are interpreted as the results of anomalous and unsustained movement of soil or other matter, such as pieces of vegetation (for example, tumbleweeds) or by movement of perched grains, in such a way that consistent movement is not produced.

Threshold friction velocities for the other sites were similarly identified and are given in Table I. Values for the unvegetated threshold friction velocities were determined in our laboratory wind tunnel runs of samples of the loose surface sandy soil taken from the sites (Jornada and Yuma) or from *in situ* field measurements on the vegetation-free surface (Shaartuz).

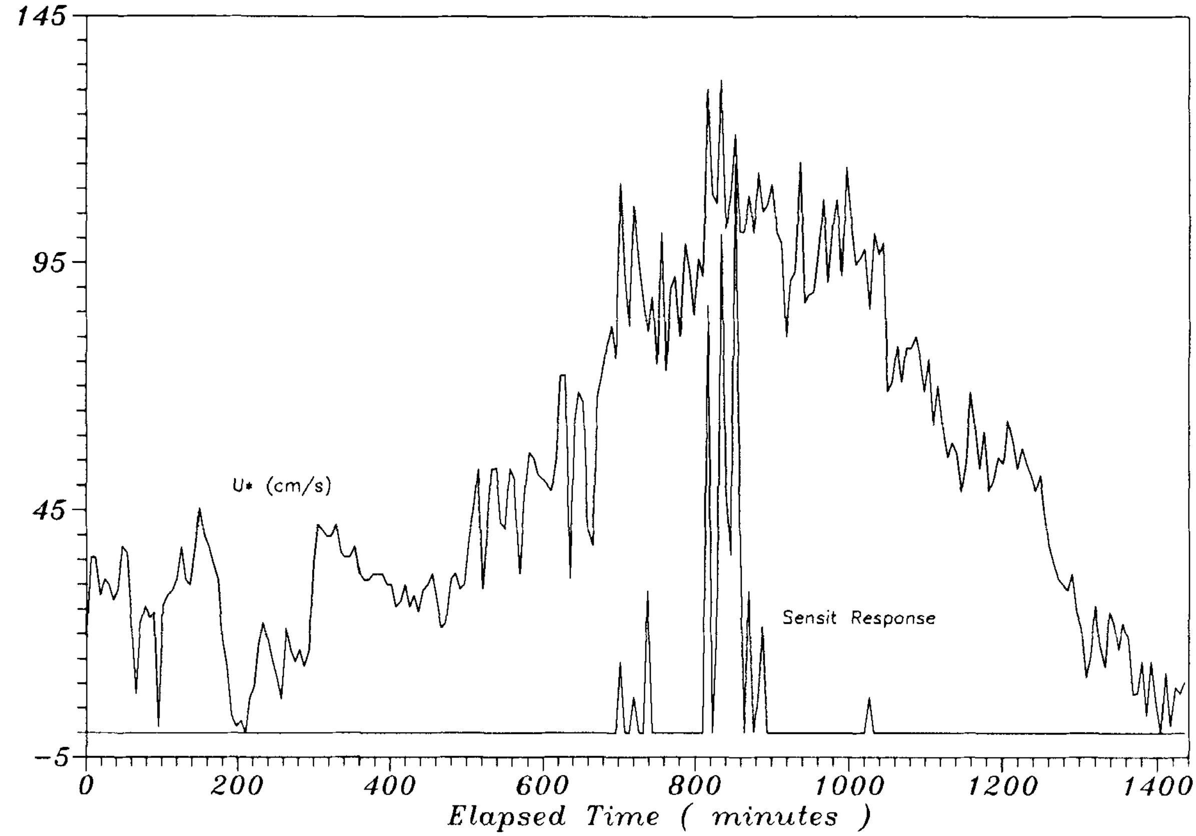

Figure 5. Plot of 'Sensit' response (relative) and friction velocity in units (cm s^{-1}) versus time in minutes at the Jornada del Muerto test site for a dust storm on 21 April, 1988

Table I. Threshold friction velocities for vegetated and vegetation-free soils at three sampling locations

Site	u_{*t} (cm s^{-1})	u_{*l} (cm s^{-1})	R	$\frac{\tau_g}{\tau}$
Jornada	30	110	0·27	0·07
Yuma	28	90	0·31	0·10
Shaartuz	60	135	0·44	0·20

DISCUSSION

Photographs of the three sites (Figures 2, 3, and 4) illustrate the relations between the vegetation cover and ratios given in Table I. The smallest value of R occurs at the site having the most vegetation and most precipitation (Jornada). The small values of R express larger vegetative sheltering; values of R closer to unity express little vegetation sheltering. The site having the least vegetation (Shaartuz) has the largest ratio. The companion paper in this issue by Musick and Gillette will couple the measurements of wind momentum partitioning with independent measurements of descriptors of the vegetation such that generalizations may be made as to the momentum partitioning properties of various types of plants.

CONCLUSIONS

The partitioning of wind momentum between that absorbed by vegetation and that absorbed by loose soil lying between the plants may be calculated by determining threshold friction velocities, both for the bare soil without vegetation present and for the vegetated soil along with the fraction of bare soil to total area. Threshold friction velocity for loose, bare soil may be determined with a small laboratory wind tunnel or *in situ* in specially prepared areas of bare soil in the field. Threshold friction velocity for the natural system of vegetation and erodible soil may be determined in the field by using automated sensors for wind and wind erosion. The use of automated sampling equipment is highly desirable because for surfaces that are even slightly vegetated compared to unvegetated surfaces, the number of wind erosion events are relatively rare and separated by long periods of time.

The ratio of threshold friction velocities for the bare soil to that for the naturally vegetated surface were measured in the field. Measured values of the above ratio were low for our most vegetated sites and nearer unity for the more sparsely vegetated site.

ACKNOWLEDGEMENTS

The authors are grateful to the late P. R. Owen for his encouragement and suggestions. This work has been partially supported by the National Oceanic and Atmospheric Administration as part of the National Acid Precipitation Program. The National Center for Atmospheric Research kindly allowed us the use of their calibration wind tunnel. The field work was done in cooperation with the US Geological Survey Desert Winds Project, with partial support from the National Aeronautics and Space Administration Interdisciplinary Research Program in Earth Sciences–Land Surface Climatology.

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