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FIELD EVALUATION OF RELATIONSHIPS BETWEEN A VEGETATION STRUCTURAL PARAMETER AND SHELTERING AGAINST WIND EROSION

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ABSTRACT

Measurements of natural vegetation canopies and of threshold friction velocities for soil movement were made at three arid and semiarid field sites. Threshold friction velocities for the vegetated surface and for bare soil were used to evaluate the partitioning of shear stress between that absorbed by the plant canopies and that absorbed by the soil surface (this potentially causing movement of soil particles). Canopy measurements were used to estimate lateral cover (total frontal-silhouette area per unit ground area), a parameter shown by previous laboratory studies to be a good predictor of shear stress partitioning. The relationship between lateral cover and shear stress partitioning for the field sites agreed with the laboratory results of Gillette and Stockton (1989). Results indicate that the protective influence of vegetative cover against wind erosion can be successfully predicted using simple measurements of vegetation canopy structure.

KEY WORDS Wind erosion Vegetation Lateral cover Soil erosion Shear stress partitioning Arid lands Canopy structure Erosion threshold Non-erodible roughness elements

INTRODUCTION

Methods are needed for predicting erosion of soil by wind in rangeland and desert margin areas where land is not cropped. Models capable of predicting the combined effects of edaphic, meteorological, and vegetational parameters on wind erosion would be useful not only in management and reclamation of rangeland susceptible to erosion, but also in interpreting the effects of past and future climatic changes on eolian sediment transport. For example, the causes of enhanced eolian transport of dust to the Atlantic from grazing lands and other source areas in the Sahel during droughts (Prospero and Nees, 1977), could be better understood with the aid of models for evaluating the effects of drought-related changes in soil conditions, wind energy, and vegetative covering. Methods designed specifically for predicting erosion from croplands (Woodruff and Siddoway, 1965) are difficult to apply to rangelands and natural vegetation because some parameters are not easily defined in a rangeland context.

Plant canopies shelter erodible soil surfaces from wind erosion by acting as aerodynamic roughness elements that absorb a portion of the total shear stress imparted by the wind. Methods are needed to predict the degree of sheltering afforded by vegetation, and these methods should utilize vegetation parameters that can be measured by simple conventional methods or by remote sensing.

Marshall (1971) used wind tunnel experiments to determine relationships between shear stress partitioning and structural parameters of roughness-element arrays. Marshall's relationships have not been fully supported by later field observations (Ash and Wasson, 1983; Eldridge, 1988) and wind-tunnel experiments (Lyles, *et al.*, 1974; Gillette and Stockton, 1989). Quantitative field measurements of relationships between

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the degree of sheltering and vegetation structural parameters have been difficult to obtain because simple field methods for determining shear stress partitioning were lacking.

In the preceding companion paper, Stockton and Gillette (1991) describe newly developed methods for field measurement of shear stress partitioning in natural dryland vegetation. Here we examine the relationship between observed shear stress partitioning, as measured by Stockton and Gillette (1991), and simple field measurements of vegetation canopy structure. Results are compared with relationships obtained in wind tunnel experiments by Marshall (1971) and by Gillette and Stockton (1989).

SHEAR STRESS PARTITIONING

Marshall (1971) followed Schlichting (1936), in describing the overall shear stress caused by wind passing over a roughened surface, as being partitioned between stress on the roughness elements and stress on the intervening surface. This may be expressed as:

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

Where W is the overall force imparted to the roughened surface, W_r is the force on the non-erodible roughness elements, and W_g is the force exerted on the floor. For our application, the non-erodible roughness elements are plant canopies, and the floor surface is assumed to be a bed of erodible soil particles.

Several parameters are useful in expressing the effect of non-erodible elements on shear stress partitioning. These include the threshold friction velocity ratio R, which may be expressed as:

$$R = u_{*t}/u_{*l} \tag{2}$$

Where u_{*t} is the threshold friction velocity of the erodible particles in the absence of vegetation, and u_{*l} is the threshold friction velocity with vegetation present.

Another parameter is the shear stress ratio, or fraction of total momentum flux going to the erodible particles:

$$1 - [W_r/(F\tau)] = (\tau_g/\tau)(F'/F) \tag{3}$$

Where F is total floor area, F' is floor area not covered by roughness elements, τ is total shear stress on the roughened surface, and τ_g is shear stress on the exposed floor. The derivation of this expression is given in the companion paper (Stockton and Gillette, 1991).

Marshall (1971) found an additional expression for shear stress partitioning useful for conveniently determining the point at which stress on the exposed floor is essentially rendered negligible by a sufficient amount of non-erodible roughness elements. This 'shear stress partition parameter' can be defined as:

$$1 - [W_r/(F\tau)]^{0.5} \tag{4}$$

Marshall (1971) characterized roughness element arrays by their 'lateral cover' L_c, defined as the ratio of total frontal-silhouette area of roughness elements to total floor area, and experimentally determined relationships between shear stress partitioning and L_c. The shear stress partition parameter (Equation 4) was found to increase linearly with $\log_{10}(1/L_c)$ above a threshold, and this threshold value of $\log_{10}(L_c)$ was used to determine the critical value of L_c necessary for complete protection against erosion. Marshall (1970) also showed how these relations could be used to predict the degree of protection against wind erosion provided by various amounts of shrub cover in semiarid rangeland.

Subsequent wind tunnel experiments (Lyles, *et al.*, 1974) and field observations (Ash and Wasson, 1983; Eldridge, 1988), have found soil movement occurring at levels of vegetative cover predicted by Marshall's relationships to provide complete protection. This lack of agreement prompted Gillette and Stockton (1989) to re-examine the quantitative effect of non-erodible roughness elements on shear stress partitioning. Their wind tunnel experiments yielded relationships similar in form to those obtained by Marshall (1971), but high levels of L_c were found to provide less protection than predicted by Marshall. Gillette and Stockton (1989) suggested that their techniques for determining shear stress partitioning were more sensitive than those of Marshall at high levels of L_c.

METHODS

Descriptions of the locations and the methods used to measure shear stress partitioning in the field are given in the companion paper (Stockton and Gillette, 1991) which should be consulted for details not given here.

Field site descriptions

Measurements were made at three locations: (1) the USDA/ARS Jornada Experimental Range north of Las Cruces, New Mexico; (2) south of Yuma, Arizona; and (3) near Shaartuz in southwestern Tadzhikistan, USSR. The Jornada and Yuma locations are part of the US Geological Survey's Desert Winds network of study sites, with instruments for continuous monitoring of geometeorological variables (McCauley, *et al.*, 1984; McCauley and Rinker, 1987; Breed, *et al.*, 1987). The Shaartuz region is the site of the joint US/USSR Desert Dust Experiment.

The Jornada site is on a broad, mostly sandy plain in the northern Chihuahuan Desert (Brown, 1982). Annual precipitation is about 250 mm per year, falling mostly in summer but with a secondary peak in winter. Three species account for most of the vegetative cover at this site: mesquite (*Prosopis glandulosa*), a winter-deciduous shrub; snakeweed (*Gutierrezia sarothrae*), a semi-woody sub-shrub; and dropseed (*Sporobolus* spp., mainly *S. flexuosus*), a perennial bunch grass. The larger mesquite shrubs have accumulated under their canopy a hummock of wind-blown sand up to 60 cm high, with stems sprouting from buried branches forming a 'coppice dune' (Melton, 1940; Gile, 1966). In recent years, the site has been grazed at light-to-moderate intensity by sheep and cattle.

The Yuma site is on a broad sandy plain in the lower Colorado River Valley subdivision of the Sonoran Desert (Turner and Brown, 1982). Annual rainfall is about 64 mm and has a bimodal seasonal distribution, falling mostly in winter and summer. Virtually all the perennial vegetation cover at this site is comprised of three species: creosote bush (*Larrea tridentata*), a tall evergreen shrub; white bursage (*Ambrosia dumosa*), a smaller shrub; and big galleta (*Hilaria rigida*), a perennial bunch grass. Big galleta bears renewal buds on stiff, semi-woody stems and thus has a shrub-like growth form (Turner and Brown, 1982). Ephemeral herbaceous plants may comprise a significant portion of the above-ground biomass after wet winters, but were small and sparse at the time of our measurements.

The Shaartuz site has an extreme continental arid climate with less than 120 mm precipitation per year, falling mostly in winter and spring. Vegetative cover is a diverse shrubland dominated by black saxaul (*Haloxylon aphyllum*), white saxaul (*Haloxylon persicum*), cherkez (*Salsola richteri*), and *Ephedra* spp. (there are many other less-dominant species). The surface soil at the Shaartuz site is silty, with a partial cryptogamic crust and a sparse cover of *Poa* sp., this grass being 1·0 to 5·0 cm tall.

Shear stress partitioning measurements

Evaluation of the influence of vegetation cover on shear stress partitioning required measurements of the threshold friction velocity in the presence of vegetation (u_{*l}) and of bare soil (u_{*t}). Detection of the threshold for vegetated soil was accomplished by: (a) monitoring the vertical wind profile, to obtain u_* variations with time, and (b) simultaneous monitoring with a device capable of recording the impacts of saltating particles, to detect the time of onset of saltation (see: Stockton and Gillette, 1991). Friction velocity u_*, the slope of the logarithmic wind profile above the mean maximum height of the vegetation, was measured by anemometers at heights of approximately 122 cm, 268 cm and 610 cm. Saltation was detected by a 'Sensit'[1] (trademark) erodible mass monitor, which records the impact of saltating soil particles on a ring-shaped piezoelectric crystal mounted on a stainless steel post at a height of 10·0 cm (20·0 cm at Jornada) above the surface. The 'Sensit' device is described in detail in Stockton and Gillette (1991).

Threshold friction velocity of the bare soil (u_{*t}) was determined for the Jornada and Yuma sites by laboratory wind tunnel measurements on samples of the loose, sandy surface soil taken from the sites. This procedure is valid only for extremely sandy soil not exhibiting aggregation or crusts. Wind tunnel procedures followed Gillette and Stockton (1989). At the Shaartuz site, u_{*t} was estimated *in situ* by measurements made on one occasion when the wind was aligned with a long, straight vegetation-free corridor leading to the instrumentation, and the threshold friction velocity for saltation was reached and exceeded (Stockton and Gillette, 1991).

Vegetation measurements

Vegetation measurements were made to estimate lateral cover (L_c) and the fractional area of soil not covered by plant canopies (F'/F in Equation 3). The parameters L_c and F'/F are simple to determine in laboratory wind tunnel experiments using arrays of solid roughness elements uniform in size, shape, and arrangement, but natural vegetation canopies are neither solid nor homogeneous. Our approach to practical application of shear stress partitioning theory to natural vegetation was to make a number of simplifying assumptions so that L_c and F'/F could be estimated using simple methods and a reasonably small amount of effort. Whether these assumptions are permissible for practical applications could then be determined by comparison of observed shear stress partitioning and threshold friction velocities with values predicted from field measurements based on the simplifying assumptions. Significant deviation of predicted from observed values would indicate the need for more complex models of canopy shape and for more detailed characterization of the canopies.

For our procedures we adopted the solid cylinder as our model of plant canopy shape. We calculated L_c as:

$$L_c = DS \tag{5}$$

Where D is canopy population density (number of individuals per unit area), and S is mean frontal-silhouette area per canopy, calculated from:

$$S = \frac{\sum h_i d_i}{N} \tag{6}$$

Where h is canopy height, d is canopy diameter, and N is the number of canopies measured. Canopy height was measured from the ground surface at the edge of the canopy to the maximum height of an imaginary envelope encompassing the bulk of the canopy but excluding erratic branches that sometimes extended beyond this imaginary envelope. Canopy diameter was taken as the average of the longest and shortest diameters measured across the imaginary envelope. We observed no marked directional preference in the orientation of asymmetric canopies. Adjacent individuals with substantial intermingling of their canopies were measured as a single canopy.

A sample of canopies was obtained by measuring canopies nearest to points regularly spaced along a line-transect. This procedure for selecting a sample is biased in favor of canopies at the edge of clumps if canopies are spatially aggregated (Pielou, 1969), but our visual observations indicated that neither aggregation nor variation of canopy size with position in a clump were significant enough to require the much laborius procedures required to obtain a truly random sample of individuals. Canopy population density D was estimated by counts of individuals in replicated square or rectangular plots. Plot size was 5·0 by 5·0 m for the densest populations and larger (up to 10·0 by 50·0 m) for the sparser populations.

At the Jornada and Yuma sites, measurement of L_c was stratified by species and confined to the three predominant species at each site (see site descriptions above), which we estimate to account for more than 90 per cent of L_c. Sampling each species separately permitted adjustment of plot size to accommodate large differences in population density and ensured an adequate sample of canopy dimensions for each species. At Shaartuz, the greater species diversity and time constraints prohibited stratified sampling.

In estimating the areal fraction of exposed soil (F'/F) we assumed that the imaginary cylindrical envelope enclosing each canopy extended to the soil surface. Line-intercept transects were used to estimate the areal fraction of vegetation canopy cover and F'/F was calculated as one minus the vegetation cover fraction. In line-intercept sampling the proportion of the total length of a line-transect intercepted by a cover component (e.g. plant species; bare ground) gives a measure of the cover of that component (Greig-Smith, 1964).

RESULTS AND DISCUSSION

Threshold friction velocities (from Stockton and Gillette, 1991) and canopy parameters for the field sites are given in Table I. The threshold friction velocity ratio (Equation 2), the shear stress ratio (Equation 3) and Marshall's shear stress partition parameter (Equation 4) calculated from the values in Table I are compared with the wind tunnel results of Gillette and Stockton (1989) and Marshall (1971) in Figures 1, 2, and 3.

Table I. Vegetation parameters (from this study) and threshold friction velocities (from Stockton and Gillette, 1991) for the three field locations

	L_c	F'/F	u_{*t} (cm s^{-1})	u_{*l} (cm s^{-1})
Jornada	0·28	0·65	30	110
Yuma	0·17	0·85	28	90
Shaartuz	0·12	0·90	60	135

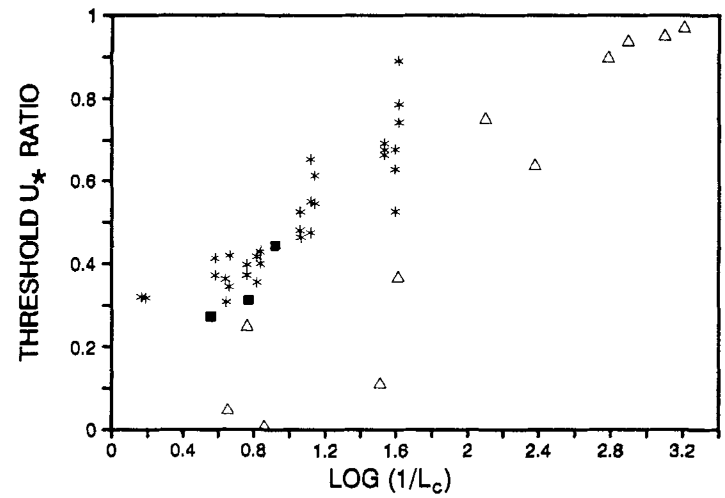

Figure 1. Threshold friction velocity ratio, u_{*t}/u_{*l} against the common logarithm of the inverse of L_c (ratio of total frontal-silhouette area to total floor area) for the field locations with natural vegetation (■) and for arrays of roughness elements used in wind tunnel experiments by Marshall (1971) (△) and by Gillette and Stockton (1989) (*)

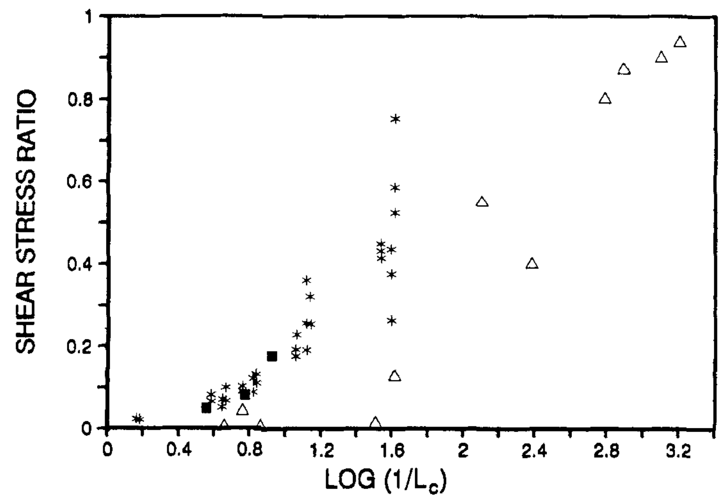

Figure 2. Shear stress ratio $1 - [W_r/(F\tau)]$, against the common logarithm of the inverse of L_c (ratio of total frontal-silhouette area to total floor area) for the field locations with natural vegetation (■) and for arrays of roughness elements used in wind tunnel experiments by Marshall (1971) (△) and by Gillette and Stockton (1989) (*)

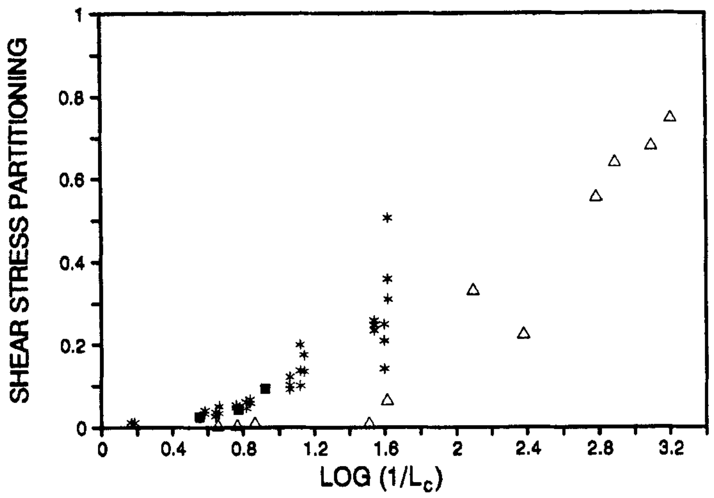

Figure 3. Marshall's shear stress partition parameter, $1 - [W_t/(F\tau)]^{0.5}$, versus the common logarithm of the inverse of L_t (ratio of total frontal-silhouette area to total floor area) for the field locations with natural vegetation (■) and for arrays of roughness elements used in wind tunnel experiments by Marshall (1971) (△) and by Gillette and Stockton (1989) (*)

Gillette and Stockton (1989) used as non-erodible elements hemispheres (half-buried spheres) of three size-classes, each mixed in varying proportions with smaller, erodible spheres also of three size-classes. In Figures 1, 2, and 3, the data from all combinations are plotted together. Marshall (1971) used cylinders varying in diameter/height ratio and hemispheres as non-erodible roughness elements. For clarity, only the Marshall data for hemispheres and for cylinders with diameter/height ratio of 2 are shown here to represent the general trend of the Marshall data. For the range of shapes used by Marshall (1971), intercepts on Figure 3 would fall between 1·4 to 1·7.

For all three measures of shear stress partitioning (Figures 1, 2, and 3), the field data agree more closely with the results of Gillette and Stockton (1989) than with the results of Marshall (1971). These sites have levels of L_c which are predicted by Marshall (1971) to be well above the threshold for complete protection, but we find that the fraction of shear stress going to the erodible surface is high enough to result in soil movement at natural wind speeds.

The establishment of threshold levels of vegetative cover, below which the land is at risk, would be a useful practical application of the results. Thresholds are particularly useful for wind erosion studies, because once erosion has begun, vegetative cover may be further reduced by the effects of erosion directly on the plants and through adverse effects on soil properties. Natural winds infrequently exceed friction velocities of 100 cm s^{-1}, so this value could be taken as the lower boundary of u_{*t} necessary for essentially complete protection against wind erosion. For sandy soils which are most at risk, u_{*t} will be approximately 30·0 cm s^{-1} (Gillette, 1988), giving a critical threshold u_* ratio of about 0·3. From Figure 1 we estimate that this critical threshold u_* ratio corresponds to a minimum L_c for full protection of approximately 0·25. Finer-textured and crusted soils with higher values of u_{*t} would have lower critical values of L_c. For grazed land, it would be prudent to use the value of u_{*t} for uncrusted soil to ensure protection even after trampling had broken up the crust. Simple models of canopy shape and measurements of canopy dimensions could be used to convert the critical L_c value to a critical value of vertically-projected canopy cover, a more conventional and easily measured vegetation parameter.

The effects of vegetation change may also be predicted. As an example, we estimate the effect of removing snakeweed from the Jornada site, where this species contributes about half of total L_c. Snakeweed populations frequently exhibit natural cyclic changes in density, and removal of snakeweed has been proposed as a means of enhancing grass production on rangelands (McDaniel, *et al.*, 1982; McDaniel, 1984). Assuming for this example that snakeweed canopies are physically removed by decomposition or other means and that compensatory increases in the size and number of canopies of other species fail to follow snakeweed removal, L_c would be reduced to about 0·14. From Figure 1, the new threshold friction velocity ratio would be about 0·45, decreasing the threshold friction velocity of the vegetated surface from 110 cm s^{-1} to about 67 cm s^{-1}. The effect of this decrease in threshold friction velocity on the annual duration of erosive winds can be evaluated using the continuously-recorded wind profile measurements made at Jornada by the USGS Desert Winds Project (McCauley, *et al.*, 1984; Breed, *et al.*, 1987) and provided to us (P. J. Helm, *pers. comm.*). In 1987, friction velocities exceeded 100 cm s^{-1} for only one 6-minute interval, but friction velocities exceeded 67 cm s^{-1} for a total of 48 h. Removal of snakeweed with no compensatory increase in other species would thus be predicted to greatly enhance the potential for wind erosion at this site.

CONCLUSIONS

Simple measurements of vegetative canopy structure may be used in combination with relationships previously derived from wind tunnel experiments to predict the partitioning of wind stress between that absorbed by the canopies and that absorbed by the intervening soil surface. If the threshold friction velocity of the bare soil is known, the estimated shear stress partitioning can then be used to assess the degree of protection against wind erosion provided by the vegetative cover.

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ENDNOTE

[1]Trademark of Sensit Co., 1226 Milner Lane, Longmont, Colorado, 80501. Use of this instrument does not constitute endorsement by the United States Government.

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