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A MICRORELIEF INDEX TO ESTIMATE SOIL ERODIBILITY BY WIND

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ABSTRACT

Surface microrelief is an effective wind erosion control measure used frequently in areas where it is difficult to maintain surface residues. The objective of this study was to develop a surface roughness index which can estimate microrelief effects on soil susceptibility to wind erosion. A soil microrelief index is developed based upon the shelter angle which is defined as the maximum angle from the horizontal between measured elevation points within a 0.3 m distance along a transect on the soil surface. Calculating this parameter for a large number of points within a 1 m^2 area and determining the cumulative distribution provides an index of surface roughness known as the Cumulative Shelter Angle Distribution. The Cumulative Shelter Angle Distribution is sensitive to tillage-induced oriented and non-oriented roughness and surface smoothing by rainfall events. Points with a shelter angle less than 15 deg are considered susceptible to impact by saltating soil particles. The effect of soil ridge height on the fraction susceptible to impact at 15 deg was similar to measured ridge height effects on soil erosion by wind.

INTRODUCTION

Soil microrelief has been shown to be an important parameter in controlling soil erosion by wind. Tillage is often used to produce ridges and soil aggregates to control wind erosion (Fryrear and Skidmore, 1985) especially in areas where it is difficult to maintain adequate surface residue cover. Römkens and Wang (1986) described four classes of soil roughness: 1) roughness due to individual particles or aggregates of 0 to 2 mm in magnitude; 2) surface variations, often referred to as random roughness, due to cloddiness on the order of 100 mm in magnitude; 3) systematic or oriented roughness due to tillage implements, 100 to 300 mm in magnitude; and 4) higher order roughness due to field topography. The second and third types of roughness are those which change most rapidly due to weathering and tillage and are subject to management.

Soil surface roughness was first described as the standard deviation of surface elevations measured at selected intervals (Kuipers, 1957). Allmaras et al. (1966) refined this concept in an index known as random roughness (RR) which has been widely used to describe surface roughness for a range of soils and tillage implements. The RR Index is determined by surface cloddiness as the effects of oriented roughness are removed in the RR calculation. Linden and Van Doren (1986) recently developed a two-parameter index which describes the surface microrelief based on the slope of the surface of clods and the mean relief. Römkens and Wang (1986, 1987) described soil microrelief based upon peak frequency and the calculated surface area per unit length.

Hagen (1988) described the processes occurring during a wind erosion event which are influenced by surface roughness. These include trapping and emission of soil particles, abrasion of soil aggregates and crusts, and the development of wind profiles. While each of the roughness indices previously discussed contain part of what is perceived necessary for evaluating surface roughness effects on wind erosion, no one index contained all the information needed. A surface microrelief index which is sensitive to factors affecting wind erosion must meet several unique requirements. The index should be sensitive to management parameters such as tillage, weather variables such as rainfall, and should be responsive to aspect because wind direction can be highly variable. Both oriented and non-oriented surface microrelief must be represented because wind erosion is often affected greatly by local microrelief maximums.

Surface roughness effects on saltating soil particles and aggregates are especially important in the prediction of wind erosion. It has been shown that wind erosion often does not begin until loose erodible particles are lying on the soil surface (Fryrear, 1984). The loose particles provide the initial materials to begin the wind erosion process. The loose materials are moved from their initial position by lift and drag forces generated by wind shear on the soil surface (Chepil and Woodruff, 1963), and blown downwind where they eventually strike the soil surface. At this time, the particles may either be trapped, or rebound and may dislodge other soil particles. The point of impact is determined by the jump length, the angle of descent, and the surface roughness.

Sorensen (1985) reported the mean jump length for a 300 μm sand, with a friction velocity of 0.90 m s^{-1}, was < 0.3 m. Sorensen (1985) also determined probability functions of impact angles. Impact angles averaged about 15 deg which agrees closely with other reported impact angles (White and Schulz, 1977; Nalpanis, 1985). The impact angles reported are similar to those reported for maximum soil abrasion (Hagen, 1984). Surface roughness

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influences the impact point by intercepting some particles and sheltering portions of the soil surface.

The objective of this article is to describe a surface roughness index that is sensitive to tillage and rainfall and can be used to estimate soil susceptibility to wind erosion.

METHODS

Soil surface elevation data was collected using a soil contacting microrelief meter. The microrelief meter was a pin-type meter which electronically recorded the distance from an arbitrary starting point until the soil was contacted by a pin with an accuracy of about 1 mm. The arbitrary starting point was fixed for a given plot. Measurements were made along a 1 m transect perpendicular to the tillage direction with 40 pins, 25 mm apart. Twenty rows, 50 mm apart, were recorded which resulted in a grid of 800 surface elevations in a 1 m^2 area. Differences in measured surface elevations were corrected to remove the effect of the arbitrary datum so that only soil microrelief was represented. Ridge heights were determined from the difference in the average elevation measured parallel to tillage marks. Ridge spacing was determined by the mean distance between elevation maximums.

Surface elevation data was collected on bare soil after tillage and after rainfall had modified the soil surface on three soils in west Texas: Amarillo fine sandy loam (Fine-loamy, mixed, thermic Aridic Paleustalfs); Amarillo loamy fine sand (Fine-loamy, mixed, thermic Aridic Paleustalfs); Acuff fine sandy loam (Fine-loamy, mixed thermic Aridic Paleustolls). Tillage included: sweep cultivation which creates a relatively smooth surface with 50 to 100 mm ridges; Lilliston* rotary hoe-sweep cultivation which creates a relatively smooth surface but preserves large existing ridges; and bedding with a lister implement, which creates a cloddy surfaces with ridges up to 300 mm high at 1 m intervals. Surface microrelief data was collected after tillage and after rainfall (5 mm to 103 mm) had modified the soil surface.

INDEX DEVELOPMENT

A soil microrelief index was developed based upon a shelter angle concept – the minimum angle from horizontal a particle must descend in order to strike a given location. The descent angle for a given point was determined by calculating the maximum angle from horizontal between a vertex point and adjacent measured points on the soil surface in a given direction. The angle for a vertex point and an adjacent point was calculated as the arctangent of the ratio between elevation differences and the horizontal distance separating the two points (Fig. 1). This procedure was repeated, retaining the same vertex point, for all other points along a transect in a given direction within a horizontal distance, termed the influence zone, of 0.3 m. The maximum angle was retained and defined as the shelter angle for that individual vertex. This procedure was repeated, incrementing the vertex point and influence zone one point, across the transect. Therefore, each measured point has a shelter angle associated with it except for those points near the edge of the plot where the influence zone extended beyond the plot. For points with a negative shelter angle, which indicates the vertex had a greater elevation than any other point in the influence zone, the shelter angle was set to zero. Therefore, low shelter angles are relatively exposed, a particle could descend at a very small angle from horizontal and strike the vertex. Large shelter angles would be relatively protected.

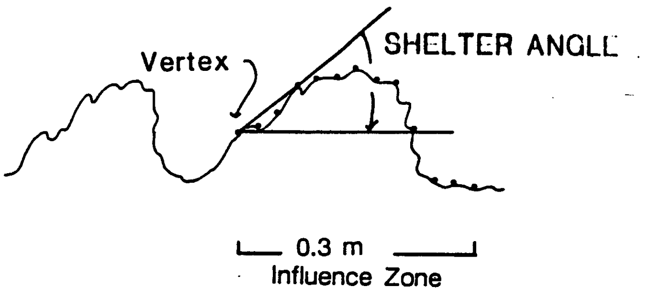

Figure 1–Surface roughness schematic illustrating the shelter angle and influence zone.

The shelter angle for a given vertex represents only that point. To represent the entire surface, many shelter angles must be considered. This was accomplished by plotting the cumulative shelter angle distribution (CSAD), the fraction of shelter angles less than a given angle vs. shelter angle. From the CSAD, the fraction of the measured points with shelter angles equal to or less than an arbitrary angle is easily determined and provides an estimate of the fraction of the surface (SF) susceptible to abrasion by particles descending at angles less than the selected angle.

A FORTRAN computer program (available from the senior author) was used to calculate the shelter angles. Several parameters used in the shelter angle calculations were selected arbitrarily or resulted from the constraints of the microrelief meter used to collect the surface elevations, specifically, the influence zone length and measurement spacing. The influence zone length may affect the cumulative shelter angle distribution by excluding some elevation maxima from consideration for a given vertex, as only points measured within 0.3 m of the vertex are considered in the calculation. The effect of influence zone length was tested by calculating shelter angles with a 0.2, 0.3, and 0.4 m influence zone. A smaller influence zone length resulted in a slightly higher zero intercept. With a larger influence zone, the intercept approached the origin. The effect on the rest of the cumulative distribution curve was small, indicating that most of the calculated maximum shelter angles were determined by roughness occurring within 0.2 m of the vertex.

Measurement spacing affects the shelter angle calculation in two ways, altering the horizontal distance between measurements and changing the number of elevation heights measured in a unit area. The effect of grid spacing was tested on 12 plots by determining the CSAD perpendicular to tillage at pin spacings of 25, 50, and 75 mm increments by using every point, alternate, or every third point, respectively. This resulted in shelter angle calculations for 600, 300, and 200 points m^{-2} with 11, 5, and 3 points in the influence zone for each shelter angle determination. The SF with a 15 deg shelter angle (SF_{15}) or

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*Use of product names is for identification purposes only and does not imply endorsement by the USDA-Agricultural Research Service.

TABLE 1. Mean surface fraction at a 15 degree shelter angle and coefficient of variation (%) for three grid spacings

Date	Surface modifier	grid spacing (mm)					
		25		50		75	
24 June	Rotary Hoe	0.351	(9.2)*	0.451	(9.2)	0.483	(8.4)
14 July	Sweep	0.411	(16.9)	0.510	(19.3)	0.515	(19.4
27 July	Sweep	0.453	(12.1)	0.483	(13.3)	0.536	(16.7)
15 Sept	Rain	0.672	(19.2)	0.694	(12.7)	0.665	(12.5)

* N = 3

less was used to evaluate the effect of measurement spacing. Fifteen degrees was chosen to test sensitivity as it is about the maximum descent angle of saltating sand grains (Sorensen, 1985). Mean SF_{15} increased as grid spacing increased (Table 1). This may be caused by the fact that, as grid spacing increases, some elevation maxima will not be measured and, hence, not affect the shelter angle calculation. The coefficients of variation were only slightly different for the three grid spacings for a given date. Since SF_{15} changed somewhat with grid spacing, comparisons of SF_{15} parallel and perpendicular to tillage direction should have equal spacing between rows and columns. A uniform 0.05 m spacing will be used for all calculations for the rest of this article.

RESULTS AND DISCUSSION

Representative CSAD plots for three tillage implements, a Lilliston rotary hoe, sweep, and lister tillage implements, are presented in Fig. 2. The Random Roughness Index (Allmaras et al., 1966) was 4, 11, and 21 mm for the three tillage implements, respectively. The CSAD curve shapes were similar for all three tillage practices but had different slopes.

ORIENTED VS. NON-ORIENTED ROUGHNESS EFFECTS

The CSAD is representative of the surface for the direction in which the shelter angles were calculated. The effect of oriented and non-oriented roughness can be determined by plotting the shelter angles calculated in different directions, i.e., parallel and perpendicular to tillage. It was assumed that the effect of ridging would be minimal in the parallel direction and the CSAD would represent non-oriented roughness. The effect of oriented roughness was determined by calculating shelter angles for transects perpendicular to tillage. The CSAD calculated perpendicular to tillage contains both random and oriented roughness effects. Therefore, the oriented roughness, or ridge effect (RE), is the difference in the two curves. A typical example of shelter angle distributions parallel and perpendicular to sweep tillage with 74 mm ridges is presented in Fig. 3. The difference in the cumulative shelter angle distribution due to orientation is an important factor for wind erosion prediction as surface protection can result from both cloddiness and oriented roughness. The amount of wind erosion which occurs is often determined by the orientation of the wind in respect to ridges (Fryrear, 1984). Cloddiness alone may not be adequate to protect the soil surface.

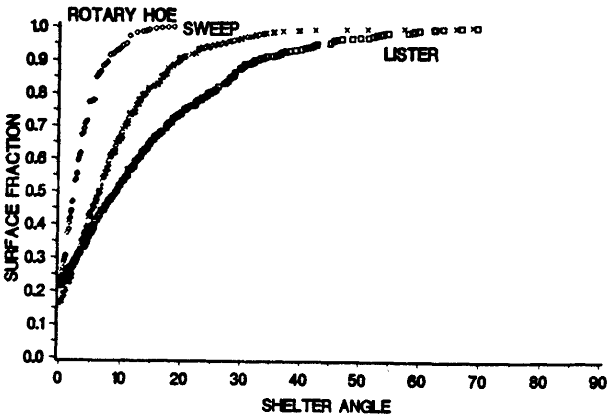

Figure 2–Representative Cumulative Shelter Angle Distributions (CSAD) calculated parallel to tillage for three tillage implements.

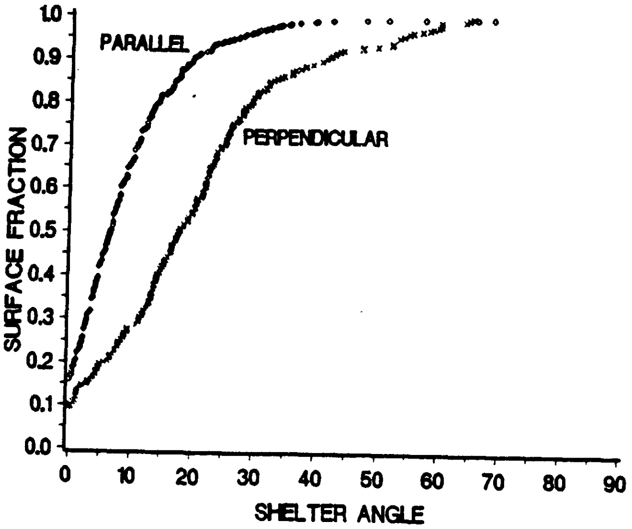

Figure 3–CSAD calculated parallel and perpendicular to tillage for a surface with 74 mm ridges.

RAIN EFFECTS

Rainfall affects surface microrelief by decaying both oriented and non-oriented roughness (Zobeck and Onstad, 1987; Lyles and Tatarko, 1987). Rain generally smooths the soil surface resulting in increased susceptibility to wind erosion. Figure 4 shows the CSAD after a sweep tillage operation and after 25 mm of rain on the same surface. Rainfall moved the CSAD curve upward when calculated both parallel and perpendicular to tillage, although the results were more clearly expressed in the parallel curve. This may have been due to a greater decrease in cloddiness than in ridge height. An advantage of a ridge for wind erosion control would be that a ridge would persist longer with rain.

ESTIMATED ROUGHNESS EFFECTS ON SURFACE ABRASION

The fraction of the soil surface susceptible to impact evaluated at a maximum descent angle of 15 deg (SF_{15}) was used to estimate roughness effects on potential surface abrasion. Locations with shelter angles greater than 15 deg are assumed to be protected from abrasion. SF_{15} parallel to tillage was correlated with the Random Roughness Index (Allmaras et al., 1966). This index is an estimate of surface roughness due to cloddiness and has been determined for many tillage implement and soil combinations (Zobeck and Onstad, 1987). With a Random Roughness Index less than

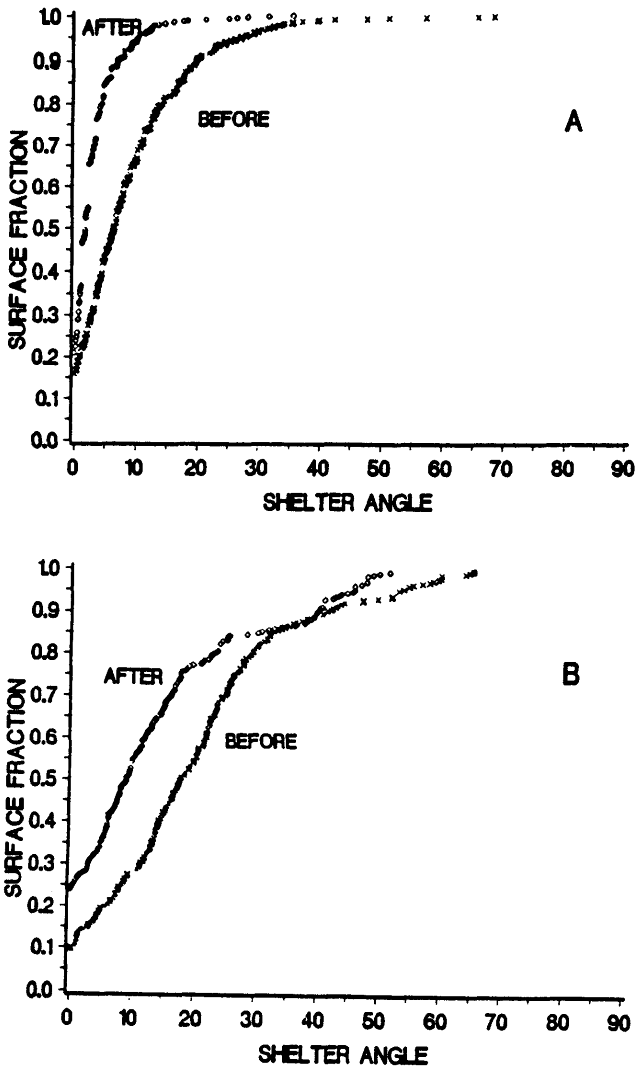

Figure 4–CSAD before and after 25 mm rainfall on a sweep tilled surface. A: Parallel to tillage; B: Perpendicular to tillage.

3 mm, the total surface was calculated to be susceptible to abrasion (Fig. 5). With a random roughness greater than 3 mm, the fraction susceptible decreased curvilinearly. The relationship between SF_{15} calculated parallel to tillage and random roughness was described by the function,

$$SF_{15} = 1.0 \qquad RR<3\text{ mm}$$

$$SF_{15} = \mathrm{EXP}\{-[(RR-3)/104]^{0.63}\} \qquad RR\geq3\text{ mm} \qquad (1)$$

where SF_{15} is the surface fraction at 15 deg, and RR is Random Roughness in mm (Fig. 5). Variability increased with larger RR values, probably because the different indices respond differently to high points on the soil profile. The highest and lowest 10% of the elevation measurements are removed in the random roughness calculation (Allmaras et al., 1966). The surface high points greatly influence the shelter angle distribution, because one high point may influence the maximum shelter angle for several points. Elevation minima affect only one point as only the maximum shelter angles are retained for each vertex.

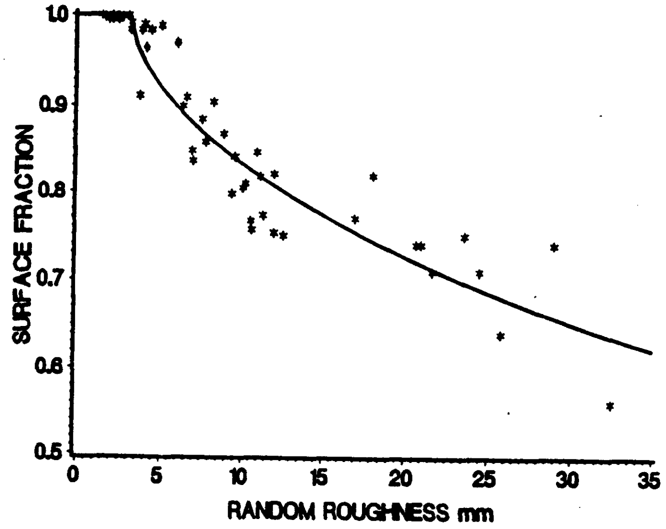

Figure 5–Random Roughness effects on the surface fraction susceptible to abrasion.

The ridge effect evaluated at a 15 deg shelter angle (RE_{15}) was determined for different tillage operations with a range of ridge heights (14 to 290 mm) and spacings (200 to 890 mm). Relationships were developed between RE_{15} and ridge height, ridge spacing, and height to spacing ratios. The best relationship was found between RE_{15} and ridge height (RH) (Fig. 6). The maximum RE_{15} was 47% of the soil surface which occurred in a lister tilled field with a 270 mm ridge. The relationship between RE_{15} and ridge height, measured in mm, was described by equation 2:

$$RE_{15} = 0.38\{1-\mathrm{EXP}[-(RH/35.4)^{1.22}]\} \qquad (2)$$

RE_{15} increased rapidly with relatively small ridges, approaching a maximum at about 100 mm beyond which additional ridge height did not greatly increase RE_{15}. This agrees with experimental results of Fryrear (1984) and Armbrust et al. (1964) which show that little additional protection is provided by ridge heights over 100 mm. The maximum predicted ridge effect was 0.38 of the soil surface. The combined effects of cloddiness and ridge height greatly reduced the predicted surface fraction susceptible to abrasion.

SUMMARY

A soil surface roughness index was developed which is sensitive to factors perceived to influence wind erosion. The basis of the proposed index is the maximum angle from horizontal between a vertex point and other measured elevation points within a 0.3 m distance along a transect on the soil surface. Calculating this parameter for a large number of points within a 1 m^2 area and determining the cumulative distribution provides an index of surface roughness best described as the Cumulative Shelter Angle Distribution. The Cumulative Shelter Angle Distribution is sensitive to tillage-induced oriented and non-oriented roughness and rain effects on surface roughness. Soil surface exposure to abrasion by saltating soil particles was estimated by determining the fraction of the surface with a shelter angle less than 15 deg – the descent angle of saltating sand particles. The fraction of the surface susceptible to abrasion decreased with increased cloddiness

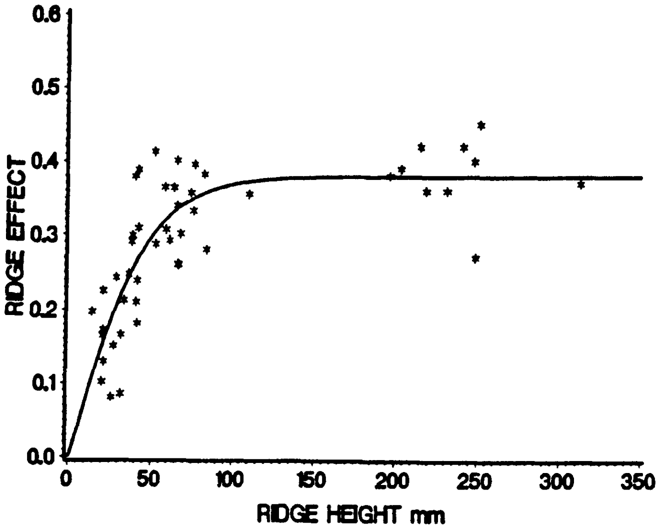

Figure 6–Variation in the ridge effect evaluated at 15 deg with ridge height.

as measured with the Random Roughness Index. The effect of soil ridges on the estimated surface fraction susceptible to abrasion was similar to measured ridge effects on soil erosion by wind.

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