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Selection of a Parameter Describing Soil Surface Roughness

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ABSTRACT

The microrelief of the soil surface, termed soil surface roughness, affects water movement into a soil profile as well as seedling germination in the seedbed. When analyzing surface roughness, the selection of a measurable, physically significant parameter describing roughness is critical. An evaluation was conducted on eight roughness parameters, including maximum peak height, a microrelief index (the area per unit transect length between the measured surface profile and the least-squares regression line through all measured positions of the transect), peak frequency, and MIF (the product of the microrelief index and peak frequency). The objective of the study was to select the parameter being the best descriptor of soil surface roughness. An automated, noncontact profiler was used to obtain surface profiles along transects, 5-cm apart, of 1-m by 1-m plots after a cultivation and a simulated rainfall application at each of three different stages of soybean [*Glycine max* (L.)] development. For each cultivation, surface profiles were obtained on bare plots before rainfall and on adjacent vegetated plots after rainfall. The common logarithm of the MIF parameter was selected as the best descriptor of surface roughness because of its sensitivity to simulated rainfall as a source of variation, and its consistent response to such rainfall. MIF can also account for spatial dependency and can be measured relatively precisely.

SOIL SURFACE ROUGHNESS is an important soil characteristic which affects hydrologic and hydraulic properties of the soil surface. Some recent studies have demonstrated relationships between surface roughness and infiltration (Moore et al., 1980), erosion (Johnson et al., 1979), runoff (Foster et al., 1984; Onstad, 1984), and radiant energy transfer (Linden, 1982).

In spite of its importance, surface roughness remains a characteristic not well defined. The attention that roughness has received is perhaps not enough when viewed in relation to its importance. This may be, in large part, due to the lack of a quantitative, physically significant parameter that can adequately describe soil surface roughness.

Several parameters have been proposed to obtain exact descriptions of surface roughness. Kuipers (1957) proposed an expression

$$R = 100 \log s \qquad [1]$$

where s was the standard deviation (a measure of sample variation) of surface elevations measured along 20 2-m transects. While Kuipers' R parameter was adjusted for slope, it was not adjusted for tillage tool marks. Later, Burwell et al. (1963) utilized a parameter which was calculated as the standard deviation of the natural logarithms of 400 height measurements taken with a point gage on a 1-m by 1-m plot with a 5.1-cm by 5.1-cm grid spacing. Their parameter was adjusted for the effects of tillage tools but not, it appears, for field slope. Subsequently, Allmaras et al. (1966) used an index termed random roughness s_y which was given as

$$s_y \simeq s_x \bar{h} \qquad [2]$$

where s_y was an estimate of the standard deviation among the measured heights, $\bar{h}$ was the mean height, and s_x was the standard deviation of the natural logarithms of the 400 height measurements following adjustments to mathematically remove the effects of tillage tool marks and slope. Currence and Lovely (1970) evaluated a number of roughness indices, including that of Allmaras et al. (1966). They, along with Dexter (1977), concluded that indices which incorporated a standard deviation or variance of height measurements, showed the most promise for describing soil surface roughness.

Unfortunately, few if any of the roughness indices used or evaluated have detailed physical significance. For instance, none directly measure elevation extremes or the frequency with which aggregates or clods occur along a transect or on a given area. Recently, additional roughness parameters with physical significance have been proposed. A microrelief index (MI) introduced by Römkens and Wang (1987) was defined, for each transect, as the area per unit transect length between the surface profile and the regression line through the measured elevations. In another manuscript, Römkens and Wang (1986a) proposed an improved roughness parameter that can be defined as

$$\text{MIF} = \text{MI} \times \text{FREQ} \qquad [3]$$

where MI is the microrelief index (mm) and FREQ is the peak frequency (mm^{-1}), the number of elevation maxima per unit transect length. They found this unitless MIF parameter to reflect the effects of both clod size and clod frequency for different tillage systems.

To consider other surface properties that might be important in describing the configuration of the soil surface, several parameters were selected for further study. These parameters included:

a. Two parameters reflecting elevation extremes,
   1. maximum peak height (PKHT), and
   2. maximum depression depth (DEDEP).
b. Two parameters representing frequencies of elevation maxima,
   3. peak frequency (FREQ), and
   4. FREQ/PKHT (FHT).
c. Four parameters containing a direct measurement of the area between a measured profile and its reference datum,
   5. microrelief index (MI),
   6. MI/PKHT (MIHT),
   7. MI/FREQ (MIOF), and
   8. MI × FREQ (MIF).

The reference datum for all the parameters was taken

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to be the regression line of Römkens and Wang (1986a) used to compute the microrelief index.

Hence, the objective of this study was to select as the best physically based descriptor of soil surface roughness that parameter whose values (i) were most sensitive to variation in soil surface roughness due to vegetative cover, simulated rainfall, and both factors concurrently, (ii) reflected a consistent response to changing conditions, and (iii) accounted for differences in elevations all along transects of experimental plots rather than elevations taken on grids of various dimensions.

METHODS AND MATERIALS

Field Operations

The study was conducted in 1984 on a Leeper clay loam (a fine, montmorillonitic, nonacid, thermic Vertic Haplaquept) of 0.5% slope (Garber, 1973) at the Northeast Mississippi Branch Exp. Stn., Verona, MS. Details of the experimental conditions have been given elsewhere (Lehrsch, 1985; Lehrsch et al., 1987 and 1988). The plots were arranged in a split-plot design with cultivations as main plots and with surface conditions—bare or vegetated—as subplots. Surface conditions were assigned randomly within each of the main plots. Cultivations, however, could not be fully randomized among the main plots because of the experimental constraint of measuring roughness on plots at lower elevations before their surfaces were affected by runoff from rainfall applications at higher elevations. The 12.2-m by 9.1-m main plots were arranged in a complete block design and each treatment combination was replicated four times.

Primary tillage was performed with a V-frame subsoiler equipped with parabolically curved shanks 1-m apart operated at a depth of 0.2 to 0.25 m. Secondary tillage was performed using a disk and a seedbed conditioner, an implement comprised of field cultivator teeth, rolling cutter blades, spike tooth harrow sections, and a drag bar. Soybeans were subsequently planted in 0.76-m rows with a John Deere Soybean Special planter[1] on two dates. Replications I and III were planted on 6 June and replications II and IV on 15 June. The difference in planting date was necessitated by the fast growth of the soybeans relative to the capability of taking elevation measurements.

[1] Trade names are included for the benefit of the reader and do not imply endorsement of or preference for the product by the USDA or Mississippi State Univ.

Table 1. Treatment summary.

Treatment	Surface cover†	Sequence of operations before elevations were measured
0‡	Bare	Cultivated ≃ 3 July, vegetation and residue removed, rainfall applied
1‡	Bare	Cultivated ≃ 3 July, vegetation and residue removed
1	Veg	Cultivated ≃ 3 July, rainfall applied, vegetation and residue removed
2§	Bare	Cultivated ≃ 3 July and ≃ 25 July, vegetation and residue removed
2	Veg	Cultivated ≃ 3 July and ≃ 25 July, rainfall applied, vegetation and residue removed
3¶	Bare	Cultivated ≃ 3 July, ≃ 25 July, and ≃ 7 August, vegetation and residue removed
3	Veg	Cultivated ≃ 3 July, ≃ 25 July, and ≃ 7 August, rainfall applied, vegetation and residue removed

† Bare = bare subplot, Veg = vegetated subplot.
‡ First cultivation (≃3 July).
§ Second cultivation (≃25 July).
¶ Third cultivation (≃7 August).

Cultivation, consisting of a single pass of a rear-mounted, six-row cultivator traveling approximately 1.43 m s^{-1}, occurred three different times during the soybean growing season. The first occurred when the soybeans were at either the V-2 or V-3 vegetative growth stage (Fehr et al., 1971), the second at the V-7 or V-8 growth stage, and the third at the V-10 or V-11 growth stage. On the cultivator, three sweeps, each 22-cm wide and operated at a nominal depth of 6 cm, were positioned between each row. From one cultivation to another, natural rainfall was permitted to strike plot surfaces.

Surface elevations were measured on main plots designated as Treatment 0 or 1 after the first cultivation, Treatment 2 after the second cultivation, and Treatment 3 after the third cultivation (Table 1). On the plots for which elevation measurements were to be taken after the first cultivation; elevations were measured twice, once before a rainfall application and once after a rainfall application. Hence, the same plot was designated as either Treatment 1 (before rainfall) or Treatment 0 (after rainfall), Table 1. Note, of the plots that were cultivated only once (≃3 July, Table 1), simulated rainfall was applied to plots with a soybean canopy (Treatment 1, Veg.) and to plots with no soybean canopy (Treatment 0, Bare). All other plots subjected to simulated rainfall had a canopy when rainfall was applied.

Immediately after a plot was cultivated for the last time, a representative 1-m by 1-m subplot was chosen. It was situated such that the subplot's centerline laid directly between two soybean rows. No effort was made to locate the subplot in either a trafficked or nontrafficked midrow, principally because elevation measurements were always to be taken after cultivation.

Immediately after cultivation, the cover provided by the soybean canopy of the subplot was determined. On a 20-cm by 25-cm print developed from a picture (taken from a 3-m height) of the canopy, a planimeter was used to determine the percentage of the soil surface covered by the soybean canopy.

This representative subplot was a "bare" subplot (Table 1), that is, a subplot (for Treatments 1, 2, and 3) in which soybeans were growing when it was last cultivated but to which no simulated rainfall was applied. Bare, then, refers not to vegetation but rather to the absence of simulated rainfall. After the soybeans in this subplot were clipped at the soil surface, surface elevations on the subplot were measured using an automated, noncontact profiler (Römkens et al., 1986). The device operated on the principle of reflectance of an infrared light beam. To eliminate interference caused by the infrared component of sunlight, all elevation measurements were made after sundown. Also, to ensure a uniform albedo, all vegetation including crop residue and standing soybeans was removed from every subplot prior to using the profiler. Elevations were measured on transects spaced 5-cm apart and perpendicular to the soybean rows. Thus, the microrelief of the entire 1-m by 1-m subplot was measured in 21 transects.

The elevation measurements that were taken on the bare subplot immediately after cultivation served as a baseline for subsequent elevation measurements of an adjacent freshly cultivated "vegetated" subplot (Table 1). A vegetated subplot was a subplot having little or no residue directly on the soil surface but having soybean plants present with their canopies in place above the soil surface when simulated rainfall was applied. After a picture was taken of this vegetated subplot's soybean canopy, a dual-nozzle rainfall simulator resembling that of Meyer and Harmon (1979) was set over the subplot. The 80 150 Veejet nozzles on the simulator produced, according to Meyer and Harmon (1979), rainfall having an impact energy of 2750 kJ (ha cm)$^{-1}$ and a modal water drop diameter of approximately 2.2 mm. With the soybeans still in place, simulated rainfall at 5 cm h^{-1} was

Table 2. The frequency distributions of the eight roughness parameters.

Treatment	Surface cover†	Transformation applied	Frequency distribution‡							
			PKHT	DEDEP	FREQ	FHT	MI	MIHT	MIOF	MIF
0	Bare	None	A	A	N	A	A	N	A	A
		Log	N	N	N	N	N	N	N	N
1	Bare	None	A	N	N	N	A	N	A	N
		Log	A	N	N	N	N	A	N	A
1	Veg	None	A	A	N	N	A	N	N	N
		Log	A	N	N	N	N	N	N	N
2	Bare	None	A	N	A	N	N	N	A	N
		Log	N	N	N	N	N	N	N	N
2	Veg	None	A	A	N	A	N	N	N	A
		Log	N	N	N	N	N	N	N	A
3	Bare	None	A	A	N	N	A	N	A	A
		Log	N	N	N	N	N	N	N	N
3	Veg	None	N	N	N	N	N	A	N	N
		Log	N	N	A	N	N	N	N	N

† Bare = bare subplot, Veg = vegetated subplot.
‡ At $\alpha = 0.05$, N indicates the distribution did not differ from a normal distribution while A indicates that the distribution did differ from a normal distribution. Sample sizes ranged from 77 to 84.

applied for 1 h to the vegetated subplot. The soybean plants were then clipped at the soil surface and the subplot was covered with elevated plastic to prevent natural rainfall from affecting the surface. As soon as possible, elevation measurements were made on this subplot.

Data Handling

The measured elevations, having been recorded on cassette tapes in the field, were corrected for tracking height ($\simeq$14 mm) and hysteresis ($\simeq$5 mm) using the technique of Römkens et al. (1986) with only minor modifications. The data were subsequently converted to distances in the horizontal and vertical directions. For each 1-m-long transect, elevation readings, recorded at an approximate 3-mm horizontal spacing, were linearly interpolated without smoothing to yield 200 surface elevations at an exact 5-mm horizontal spacing. A plane view, then, showed 21 transects with 200 points each perpendicular to both the direction of traffic and the soybean rows. Finally, systematic variations in surface elevation caused by row furrows or implement tracks were eliminated (Römkens and Wang, 1986a) from each subplot's data by first regrouping the data from 21 sets (one set for each transect) of 200 points each to 200 sets of 21 points each. Least squares regression was then used to fit a straight line through the 21 points of each of the 200 data sets. The fitted line was assumed to estimate the surface elevation in the absence of soil cloddiness for each of the 21 points along the line. The final step consisted of subtracting for each point the estimated elevation from the measured elevation.

Roughness parameters for each subplot were calculated for each of the 21 data sets, one set for each transect and each set containing 200 points of adjusted elevation (that is, elevation corrected for tracking height, hysteresis, and row furrows). Before a number of the roughness parameters such as PKHT and MI could be calculated for each transect, a reference datum was needed. That datum was obtained using linear least squares to fit a straight line through the 200 points of each transect.

Parameter Selection

The parameters were evaluated to identify those having the most potential to describe soil surface roughness. Upon examination, the frequency distributions of the eight roughness parameters were found to resemble log-normal distributions (Lehrsch et al., 1988). In Table 2, the results of a Lilliefors test (Conover, 1980) indicate that a common logarithmic transformation of the eight roughness parameters caused their frequency distributions in over 89% of the cases to not differ significantly from the normal distribution. Since the parameters were to be normally distributed for a subsequent analysis of variance, common logarithms of the eight parameters were calculated and used in all subsequent analyses. The spatial variation of all of the logarithmically transformed roughness parameters has been reported elsewhere (Lehrsch et al., 1988). One of the most important reasons that a spatial variability analysis was performed was to obtain, for each roughness parameter (RP) on each plot, a zone of influence (ZI). This ZI was the horizontal distance within which measurements of a particular RP were spatially dependent. The ZI thus indicated the minimum spacing between transects that was necessary to obtain statistically independent measurements of that RP. Using the ZI for each RP on each subplot, independent transects were grouped (Lehrsch et al., 1988) and a mean for the appropriate RP was determined. The roughness parameter selected as best describing soil surface roughness was the parameter that (i) showed the most sensitivity to variation in surface roughness caused by rainfall and vegetative cover, (ii) reflected a consistent response to changes in those factors, and (iii) showed consistency among sets of spatially independent transects. That parameter was then compared using correlation analysis to the roughness parameters of Kuipers (1957) and of Allmaras et al. (1966). Random roughness (Allmaras et al., 1966) was approximated using the analysis of variance procedure of Linden and Van Doren (1986).

RESULTS AND DISCUSSION

Selection of a Roughness Parameter

To compare RPs from plot to plot, means for each of the RP's were computed for each subplot. For subplots where a particular RP showed no spatial dependence, its mean was calculated using all 21 transects. Spatial dependence was the dependency of or correlation among the values of a particular RP calculated for adjacent transects. For subplots where a particular RP exhibited spatial dependence, however, its mean was calculated using only a subset of the original 21 transects. On such a subplot, the subsets that were assembled consisted of transects separated by distances equal to or larger than the ZI value for the parameter on that subplot. For a particular subplot, one might expect the subset means to be the same because they were calculated for the same subplot.

Table 3. MIF measured on sets of independent transects from Treatment 1, Replication 2, Bare.

		Statistic		
Transect set	n	Subset mean	SD†	CV, %‡
1, 4, 7, ..., 19	7	−0.845	0.064	7.57
2, 5, 8, ..., 20	7	−0.846	0.034	4.02
3, 6, 9, ..., 21	7	−0.858	0.084	9.79

† Standard deviation. ‡ Coefficient of variation.

They differed because they were calculated using the data from different transects, however. The RP to be selected as the best descriptor of soil surface roughness was to differ as little as possible among subset means within a plot. As a whole, the means of all of the RPs showed good consistency among subsets. Representative subset means are given in Table 3 for MIF measured on Treatment 1, Replication 2, bare subplot, a subplot on which the ZI for MIF was 15 cm. Table 3 shows that (i) the subset means were similar and (ii) the degree of dispersion among the values that made up each mean was also similar. For the eight RPs over the entire study, the largest difference between any two subset means within a plot was only 8.4% of the mean of that RP across all 28 plots. The RPs with the smallest to largest differences between subset means were ordered as

$$\text{FREQ} < \text{MIHT} = \text{MIOF} = \text{PKHT} = \text{MI} < \text{MIF} < \text{DEDEP} < \text{FHT}.$$

For later comparisons, the subset whose mean RP was closest to the mean for the RP over the entire subplot was chosen (Römkens and Wang, 1987).

One assumption was made in order to select one RP as the best descriptor of surface roughness. For each of the four replications, the soil surface roughness of the vegetated subplot after cultivation was assumed to be the same as the roughness of the bare subplot after cultivation. This assumption is reasonable because (i) the subplots were cultivated at the same time, hence at similar soil water contents, (ii) the subplots in each replication were separated by less than 3 m, and (iii) the soybean plants were removed from the bare subplots only after the plots were cultivated.

To select the roughness parameter which showed the greatest sensitivity to the experimental sources of variation, two approaches were used. This was because of the above-mentioned runoff constraint that limited the randomization of treatment combinations among the experimental units in the field. The first approach was to use an analysis of variance. An analysis of variance was felt to be an appropriate type of analysis because the data of the study satisfied the three main assumptions necessary for an analysis of variance (AOV), homogeneous variance, independent observations, and normality. Heterogeneous variance can be a problem if one compares, without taking precautions, means calculated using different numbers of replications (or subsamples, as the case may be). Heterogeneity of variance was handled by estimating the variance components on a single sample basis and weighting the variance components properly to obtain an estimate of the variance of the population means. In other words, the AOV was modeled considering subsampling and the means were compared in such a manner that took into consideration the unequal number of subsamples. Independence among observations was assured by selecting a split plot design and then performing the analysis and mean comparisons based upon that design. The assumption of normality was satisfied because the frequency distributions of the eight RPs were examined at the start and were found to resemble lognormal distributions (Table 2). The individual values were then logarithmically transformed so as to be normally distributed.

Table 4. Soybean canopy cover by treatment.

Treatment	Surface cover†	Canopy cover Mean	SE‡
		%	%
1	Bare§	26.2	2.8
1	Veg¶	25.9	2.5
2	Bare	64.8	2.7
2	Veg	63.2	2.5
3	Bare	74.9	1.0
3	Veg	77.3	1.2

† Bare = bare subplot, Veg = vegetated subplot.
‡ Standard error of the mean.
§ The canopy covers reported for the bare subplots of each treatment were those covers present just before all vegetation (including crop residue and standing soybeans) was removed in preparation for the elevation measurements.
¶ The covers reported for the vegetated subplots were the covers present immediately before the subplots were subjected to simulated rainfall.

The analysis was based on a split plot design with four replications and unequal subsampling. Because of the unbalanced design, a linear model was utilized (SAS Institute, Inc., 1982b)[1]. Unfortunately, because cultivations could not be randomized among main plots due to the fact that runoff would have affected the roughness of downslope plot surfaces, no valid error term was available to test cultivation as a source of variation in the values of the eight RPs. Hence, in the analysis of variance, attention was focused on the main effect of surface cover and on the interaction of cultivation with surface cover. Values of one of the RPs, MIF, measured after cultivation have been reported earlier (Lehrsch et al., 1987).

During the course of the study, simulated rainfall was applied after the final cultivation (Table 1) of each plot. Because the final cultivations of Treatments 2 and 3 were performed later in the growing season, the soybeans of these treatments were at progressively later

Table 5. Significance of surface cover and cultivation x surface cover as sources of variation in the logarithms of the roughness parameters.

	Statistical significance							
	Roughness parameter							
Source of variation	PKHT	DEDEP	FREQ	FHT	MI	MIHT	MIOF	MIF
Surface cover (Bare or Veg)	NS†	NS	*	NS	NS	NS	NS	**
Cultivation x surface cover	NS	NS	NS	NS	NS	NS	NS	NS

*,** Significant at the 0.05 and 0.01 probability levels, respectively. † NS = nonsignificant.

Table 6. Effect of simulated rainfall on MIF in the absence of a vegetative canopy.

Treatment description	Least-squares mean for MIF†
No rainfall applied	−0.759a‡
Rainfall applied	−0.822b

† A least-squares mean (Searle et al., 1980) is an estimate of the mean that would have been obtained had the experimental design been balanced.
‡ Means not followed by a common letter differ significantly at the 0.05 level (SAS Institute, Inc., 1982b)[1].

Table 7. Effect of vegetation on MIF for subplots on which simulated rainfall was applied.

Treatment description	Least-squares mean for MIF
Vegetation present	−0.796a†
Vegetation absent	−0.822a

† Means followed by a common letter do not differ significantly at the 0.05 level (SAS Institute, Inc., 1982b)[1].

stages of development. Obviously, the coverage provided by the soybean canopies increased from one treatment to another through the study (Table 4). In the analysis of variance, however, only cultivation was available as a source of variation to account for this ever changing effect of soybean canopy. Thus, the percent canopy cover was initially used as a covariate in the analysis of variance to adjust the RP means to make them what they would have been if all the percentages of canopy cover had been the same. This preliminary analysis indicated that the percent canopy cover had no effect on the statistical significance of surface cover or of the cultivation by surface cover interaction for any of the eight RPs. Hence, the percent canopy cover was omitted as a covariate in all subsequent analyses. This omission of percent canopy cover as a covariate then enabled the subsampling to be fully considered in all subsequent analyses.

Using the data from the complete study, an analysis of variance was performed on all eight RPs (Table 5). The source of variation identified as surface cover represents, within each cultivation, a comparison between bare plots that received no simulated rainfall and vegetated plots that did receive simulated rainfall. The second source of variation, that identified as cultivation x surface cover, tested for the presence of a statistically significant interaction between cultivation and surface cover. For example, an interaction would be present if the surface cover effect was different from one cultivation to another. Table 5 shows that the RPs that were significantly affected by surface cover always explicitly considered FREQ. The MIF parameter was the most sensitive to variations in surface cover.

Because random roughness (Allmaras et al., 1966) has been widely used and has been felt to be a good descriptor of soil surface roughness (Currence and Lovely, 1970), it was calculated for each of the plots of this study and its values subjected to a similar analysis of variance. But, like most of the RPs of Table 5, random roughness was not significantly affected by surface cover or the cultivation x surface cover interaction. To this parameter's credit, the influence of the simulated rainfall applied to the vegetated plots was reflected in its values, though not to a statistically significant degree.

In addition to the analysis of variance, a second approach was used to select a roughness parameter. It was a visual examination in which each RP's mean for both treatment and surface cover was compared replication by replication. As an illustration, an RP whose mean for a bare subplot was larger than its mean for a vegetated subplot in 90% or more of the cases studied, would be considered to respond not only sensitively but also consistently to surface cover as an experimental source of variation. This second approach resulted in findings similar to those of the analysis of variance. The visual examination showed that two parameters, FREQ and MIF, were sensitive to surface cover. The FREQ responded similarly in 75% of the cases while MIF responded similarly in over 90% of the cases.

Therefore, the roughness parameter MIF was identified as showing the most promise for describing soil surface roughness. A number of reasons can be given for the selection of this parameter. First, the MIF parameter showed, as did all the other RPs, good consistency among subset means (Table 3). Second, MIF was by far the most sensitive (Table 5) to the surface cover of the plots. Third, the MIF parameter responded most consistently to surface cover, responding similarly in over 90% of the cases. Also, MIF was the roughness parameter identified by Römkens and Wang (1986a, 1987) to respond to both tillage systems and rainfall.

Effect of Rainfall on MIF

The question may be raised as to whether the effects of simulated rainfall alone can be isolated from the effects of both rainfall and vegetation on soil surface roughness as measured using MIF. On four subplots of this study, with no vegetative canopy present, roughness was measured both before simulated rainfall (Treatment 1, Bare) and after simulated rainfall (Treatment 0, Bare). The analysis of data from these subplots indicated that rainfall significantly decreased the roughness of the soil surface (Table 6). The values of the MIF parameters are given as least-squares means or marginal means as they are sometimes termed (Searle et al., 1980). Least-squares means are estimates of the means that would have been obtained had the experimental design been balanced (that is, had the MIF parameter for each subplot been calculated using the same number of transects). The design was unbalanced as a consequence of the spatial dependence of MIF (Lehrsch et al., 1988). This spatial dependence led to unequal subsampling from subplot to subplot and hence, the unbalanced design. The unbalanced design prevented the use of traditional mean separation procedures such as the Duncan's or Student-Newman-Kuels' test. In SAS (SAS Institute Inc., 1982b)[1] an option was available, however, to separate means from unbalanced designs.

Effect of Vegetation on MIF

Data that were available also permitted the evaluation of the effects of vegetation alone on MIF. When simulated rainfall was applied to subplots with vegetation present (Treatment 1, Veg.) and to subplots with vegetation absent (Treatment 0, Bare), the least-squares MIF means (Table 7) indicated that vegetation exerted no statistically significant effect on soil surface roughness. This lack of significance is reasonable because the data on which this evaluation was made were obtained at the time of the first treatment (cultivation) when the vegetative canopies covered just over one fourth of the surface of each subplot (Table 4). Nevertheless, Table 7 does imply that a vegetative canopy serves to lessen the degree to which rainfall decreases surface roughness. This protection given by vegetative canopies to the roughness of soil surfaces is currently under additional study.

Comparison of MIF to Other Parameters

The MIF parameter, the Kuipers (1957) parameter, R, and the Allmaras et al. (1966) parameter, s_y, are given in Table 8. They were compared using a correlation analysis (SAS Institute, Inc., 1982a)[1]. As expected, they were positively correlated, with the simple correlation coefficients between R and s_y being 0.60, between MIF and R being 0.52, and between MIF and s_y being 0.78. Correlation between the values of R and s_y is to be expected because (i) both parameters are calculated using a standard deviation of surface elevations, and (ii) neither parameter accounts for spatial variability among the height measurements used in their calculation. The facts that the R and s_y parameters (i) do not account for spatial variability and (ii) do not explicitly consider peak frequency are in part responsible for their less than perfect correlation to the MIF parameter. All three correlation coefficients being positive indicates that, in general, all three parameters are identifying the same plots as being the roughest. However, R and s_y, while being measures of the variation of height measurements on a plot, are not so strongly affected by height differences between adjacent points and less affected by the number of peaks or depressions than is the MIF parameter. The MIF parameter, on the other hand, is sensitive to both as it is composed of the microrelief index and the peak frequency. The microrelief index accounting for height differences can be thought of as a measure of amplitude while the peak frequency as a measure of frequency (Römkens and Wang, 1986b). As such, in combination they supply a more complete description of soil surface roughness than does the parameter of Kuipers (1957) or the parameter of Allmaras et al. (1966). Table 8 shows that R did not always reveal a decrease in roughness caused by the simulated rainfall that was applied to the vegetated subplots of each treatment. On the other hand, s_y and MIF always revealed such a decrease due to rainfall. This similar response is surely a reason why the highest correlation coefficient (0.78) was found between s_y and MIF. As noted above, this consistent decrease in s_y caused by simulated rainfall (Table 8) is to that parameter's credit. Unfortunately, the magnitude of the decrease in s_y, at least in this study, could not be declared statistically significant.

In general, MIF decreased more than s_y as a consequence of rainfall (Table 8). Moreover, the standard errors of the mean associated with the values of MIF are usually half or less the size of the standard errors of the mean of the values of s_y. These smaller standard errors of the mean indicate the increased precision obtainable when in the statistical analysis, one can consider subsampling, such as is the case when MIF is used to describe the roughness of soil surfaces. This increased precision for the MIF means reveals why surface cover was found to be a significant source of variation in MIF (Table 5) but not in s_y.

Table 8. A comparison of three roughness indices, R (Kuipers, 1957), s_y (Allmaras et al., 1966), and MIF (Römkens and Wang, 1986a).

Treatment	Surface cover†	R			s_y			MIF		
		n	Mean	SE‡	n	Mean	SE	n§	Mean	SE
			cm			cm			-	-
0	Bare	4	21.44	1.90	4	0.81	0.05	59	−0.822	0.014
1	Bare	4	22.90	2.33	4	0.84	0.07	70	−0.759	0.019
1	Veg	4	23.78	4.38	4	0.82	0.04	84	−0.796	0.016
2	Bare	4	18.06	2.16	4	0.78	0.07	83	−0.788	0.016
2	Veg	4	19.12	2.52	4	0.73	0.05	70	−0.815	0.019
3	Bare	4	19.47	1.50	4	0.78	0.05	51	−0.758	0.027
3	Veg	4	17.95	4.59	4	0.70	0.03	59	−0.847	0.021

† Bare = bare subplot, Veg = vegetated subplot.
‡ SE = standard error of the mean.
§ For MIF, the total number of subsamples taken on the four replications.

CONCLUSION

Of the eight parameters studied, the common logarithm of MIF was selected as having the greatest potential for describing soil surface roughness because (i) it was sensitive to the effects of rainfall, (ii) of all the parameters, it most consistently revealed a decrease in roughness as a consequence of simulated rainfall, and (iii) it did not vary greatly in value on the same plot from one set of independent transects to another. As a descriptor of soil surface roughness, MIF offers other significant advantages. It can be calculated in such a manner so as to eliminate spatial dependency among measurements taken on the same plot. In certain situations, the increased precision with which it can be measured (Table 8) can result in certain sources of variation being found significant rather than nonsignificant. The MIF parameter has been shown (Römkens and Wang, 1986a; 1987) to vary for different tillage systems. The MIF parameter not only accounts for elevation differences between adjacent points but also explicitly considers peak frequency. Last, if one did not have access to a profiler equipped with an infrared light beam, MIF would still be directly estimable providing that surface elevations were measured at 0.5-cm spacing along 21 parallel 1-m transects, with a 5-cm spacing between transects. While a given value of MIF does not describe a unique surface configuration, the MIF parameter nonetheless represents a significant step toward such a goal.

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