Soil Surface Roughness as Influenced by Selected Soil Physical Properties[a]

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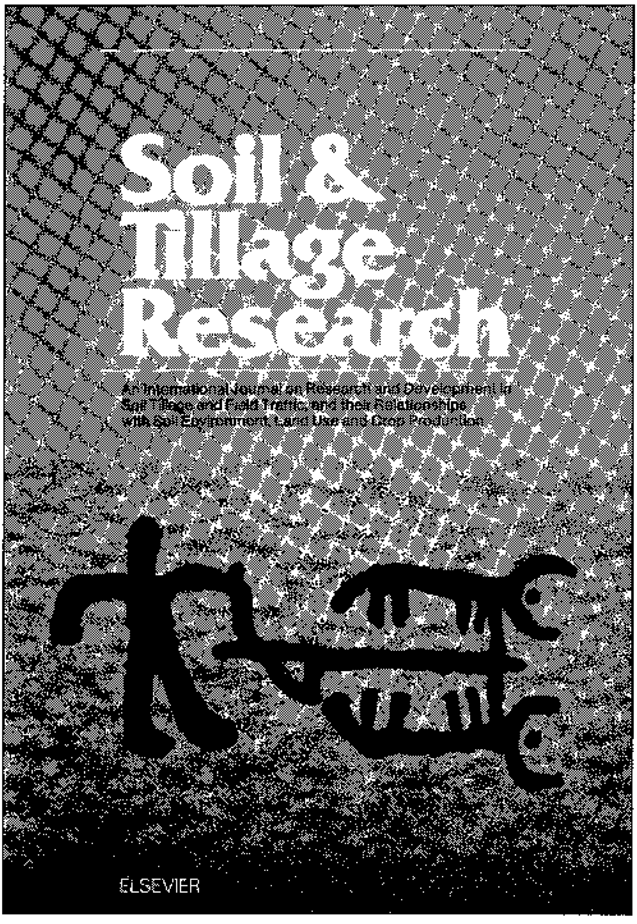

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ABSTRACT

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Soil surface roughness affects infiltration, the storage of water in depressions on the soil surface, runoff and other processes. Roughness of soil after tillage or cultivation is affected by soil factors such as soil type, soil aggregation, water content and others. Specific soil properties that determine a soil's physical reaction to tillage should be identified, so that mechanistic relationships between those properties and the resultant roughness can be developed. The objective of this study was to determine relationships between soil surface roughness, measured using an *MIF* parameter (the product of a microrelief index and peak frequency), and water content, bulk density, soil texture, wet and dry aggregate size distributions, aggregate stability, organic matter content and other soil properties, measured after each of 3 cultivations throughout a growing season. During the summer of 1984, soil physical properties at depths of 10.8 and 30.5 cm were measured prior to primary tillage, and at the surface immediately before 3 cultivations of soya beans, *Glycine max* (L.) Merr. An automated, non-contact profiler measured surface profiles along transects, 5 cm apart, of 1×1 m plots after each cultivation. With water content and dry bulk density at the soil surface ranging from 0.06 to 0.21 kg kg^{-1} and from 1.05 to 1.26 Mg m^{-3}, respectively, roughness, as the common logarithm of *MIF*, ranged from -0.758 to -0.788. Dry and wet bulk density were found to account for 64 and 52% of the variation in the *MIF* parameter, respectively. Water content at cultivation, and at -33 kPa, accounted for 21 and 22%, respectively, of the variation in surface roughness.

INTRODUCTION

Soil surface roughness refers to the microrelief of the soil surface. The roughness of the soil's surface affects infiltration, surface depression storage, runoff, evaporation, and other processes.

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The study of roughness has not received the attention it deserves, because of the difficulty of describing the configuration of the soil surface adequately (Römkens and Wang, 1985). In the past, several parameters have been introduced to describe soil surface roughness. Kuipers (1957) and Burwell et al. (1963) used the standard deviation of measured surface elevations. Allmaras et al. (1966), elaborating on the earlier work of Burwell et al. (1963), defined a random roughness index s_y as

$$s_y = s_x \bar{h} \tag{1}$$

where s_y is the standard error among heights, s_x is the standard error among the logarithms of 400 height measurements taken on a grid, and $\bar{h}$ is the mean height of the measurements. More recently, Römkens and Wang (1986) identified and used a physically significant roughness parameter which can be defined as

$$MIF = MI \times FREQ \tag{2}$$

where MIF is the product of a microrelief index (MI) defined as the area per unit transect length between the measured surface profile and the least-squares regression line through all measured positions of a transect, and a peak frequency ($FREQ$), the number of elevation maxima per unit transect length.

Using similar procedures, Lehrsch (1985) described the spatial variation of 8 roughness parameters and evaluated their potential for describing soil surface roughness. The parameters included maximum peak height, maximum depression depth, MI, and $FREQ$, not only alone but also in various combinations. He measured these roughness parameters on transects spaced 5 cm apart and found, for sets of transects each numbering from 77 to 84, that the parameters were normally distributed in 49% of the cases and log-normally distributed in 81% of the cases (some cases could be satisfactorily described using either a normal or a log-normal distribution). Using a semi-variogram analysis, he determined the spatial variation of the common logarithm of each of the roughness parameters across 1×1 m plots. He then calculated a mean value of each parameter for each plot, using sets of independent transects. After evaluating each mean roughness parameter for its sensitivity both to cultivation and to vegetative cover, he concluded that, for his conditions, the common logarithm of the MIF parameter, Eqn. (2), best described roughness when comparing the mean roughness from plot to plot or treatment to treatment. Hence, for this study the common log of the MIF parameter was used to describe soil surface roughness.

Even though relationships between soil surface roughness and particular tillage practices have been identified, inconsistencies are still present (Allmaras et al., 1966). Researchers have speculated that soil type, soil management history and soil water content at tillage may have been responsible for the inconsistent ranking of tillage treatments using random roughness indices measured after tillage. Indeed, in a subsequent paper, Allmaras et al. (1967) stated that an evaluation of the relationship between soil surface roughness, soil strength, and soil aggregate distributions would improve our knowledge of soil structural changes induced by tillage operations.

Some soil properties have been related either to soil surface roughness directly or to soil cloddiness. Soil water content, one of the most important properties, affects soil surface roughness not only directly, but also indirectly, by influencing other soil properties which in turn affect roughness. Allmaras et al. (1967) found that random roughness was greatest at low water contents, decreased as water contents increased to the lower plastic limit, and then increased again as water contents continued to increase. Water content has consistently affected the random roughness after plowing (Allmaras et al., 1967), influenced aggregate size distributions and aggregate strength (Lyles and Woodruff, 1961), and been identified (along with type of tillage) as probably the most important factor influencing soil surface conditions after tillage (Lyles and Woodruff, 1962).

Bulk density, soil texture (clay content), and aggregate size also affect soil surface roughness. As the bulk density of a sandy loam, a silty clay loam and a clay soil increased, the percentage of clods having diameters > 6.4 mm also increased (Lyles and Woodruff, 1961). They also found that clay content increased clod strength, while other researchers (Allmaras et al., 1967) found clay content to exert no consistent direct effect on random roughness. Aggregate size as visually observed has been noted (Allmaras et al., 1967) to be approximately proportional to random roughness.

Thus, with due consideration given to the research that has been conducted in the past, a number of soil properties were selected for study. Because of the relationships outlined above, water content and both dry and wet bulk density (all to be measured at cultivation) as well as soil texture were chosen. From the soil characteristics, the water content at a matric potential of -33 kPa was chosen because it approximates to the water content at the lower plastic limit, a water content found to be important by Allmaras et al. (1967). Shear strength and penetration resistance were selected, because they supply information related to the response of the soil matrix as a whole to the disruptive forces applied by the passage of a tillage tool through the soil profile. Also chosen were aggregate strength, aggregate stability, and aggregate size distribution (determined both by dry and by wet sieving). These properties have been mentioned by others (Allmaras et al., 1967) as being significant sources of variation in soil surface roughness. Finally, organic matter was selected because of its relationship to soil aggregation and aggregate stability (Baver et al., 1972). Thus, the objective of the present study was to determine relationships between selected soil physical properties and soil surface roughness measured after each of 3 cultivations throughout a growing season.

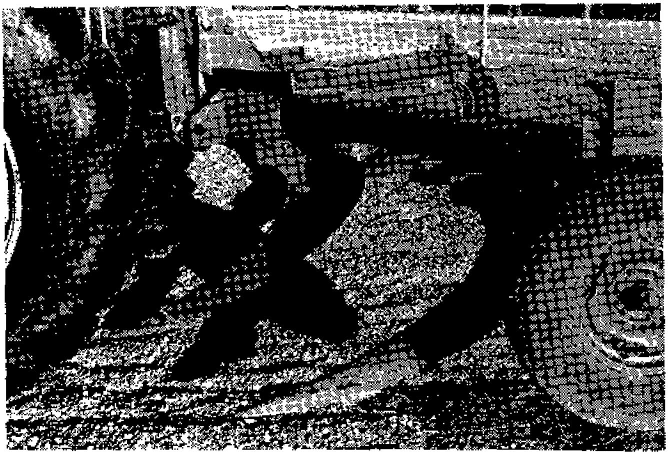

Fig. 1. A parabolic chisel.

METHODS AND MATERIALS

Field operations

The study was conducted in 1984 on 12.2×9.1 m soya bean (*Glycine max* (L.) Merr.) plots of a Leeper clay loam (fine, montmorillonitic, nonacid, thermic Vertic Haplaquept) located on the Northeast Mississippi Branch Experiment Station, Verona, MS, U.S.A. The experimental design was a complete block design with 3 treatments (each being a separate cultivation) and 4 replications. Experimental constraints, particularly runoff moving downslope after some nearby rainfall applications, limited the degree to which treatments could be randomly assigned to the field plots. Treatments were designated as Treatment 1 after the first cultivation, Treatment 2 after the second cultivation, and Treatment 3 after the third cultivation.

Primary tillage was accomplished with a parabolic chisel (Fig. 1), with shanks 1-m apart operated at a depth of 0.2–0.25 m. Secondary tillage was performed using a disk and a second implement (Fig. 2), locally referred to as a do-all, having field cultivator shanks followed by a rolling cutter-bar and a drag-harrow.

Soya beans were planted in 0.76-m rows on two dates with a John Deere Soybean Special planter[1]. Replications I and III, chosen so as to achieve a degree of randomization in the field, were planted on 6 June and Replications II and IV were planted on 15 June. The difference in planting date was necessitated by the fast growth of the soya beans 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 U.S. Department of Agriculture or Mississippi State University.

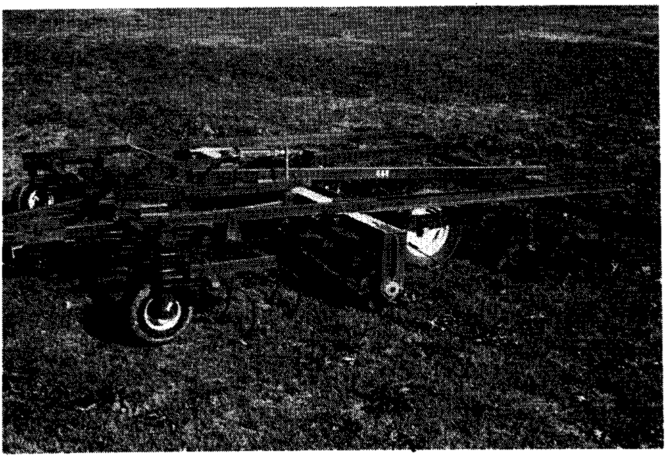

Fig. 2. A secondary tillage implement known as a do-all.

Cultivation using a 6-row cultivator traveling approximately 1.43 m s^{-1} occurred 3 times, first at the soya bean V-2 and V-3 vegetative growth stage (Fehr et al., 1971), second at the V-7 and V-8 growth stage, and third at the V-10 and V-11 growth stage. For illustration, soya beans at the V-2 vegetative growth stage would have fully developed leaves at 2 nodes on the main stem, including the unifoliate node. On the cultivator, 3 sweeps, each approximately 22-cm wide and operated at a nominal depth of 6 cm, were positioned between each row.

Soil sampling and analyses

In the spring, before primary tillage was conducted, soil samples were taken to the 34-cm depth in each plot to determine certain soil properties. A Giddings hydraulically-driven soil sampler[1] was used to take 7.4-cm diameter cores to a depth of 7.4 cm for the determination of water content and bulk density. From a core 1 cm deep and 7.4 cm in diameter, the soil water content at −33 kPa or a third bar (*WCTH*) was determined using the procedure of Richards (1965). A hand-operated, recording-type soil penetrometer (Carter, 1967) was used (Davidson, 1965) to determine the soil's resistance to penetration as a function of depth to 61 cm. Undisturbed bulk-core samples were taken, from which estimates of the soil's shear strength were later determined using an unconsolidated–undrained (quick) test (Lambe, 1951; Sallberg, 1965). Soil structure (Soil Survey Manual, 1951) was determined in the field. Disturbed samples were taken to the laboratory and air-dried before the determination of (1) a dry aggregate size distribution using the general procedure of Kemper and Che-

[1]See footnote on p. 200.

pil (1965), with the exception being that a nest of flat sieves was shaken for 10 min on a mechanical sieve shaker, and (2) a wet aggregate size distribution using the procedure of Kemper and Chepil (1965), with the exceptions being that (a) the aggregates were wet under 4-cm tension (Rhoton et al., 1982) and (b) the samples were sieved for 8 instead of 10 min.

Soil from the disturbed samples was also used to determine the strength of air-dry aggregates by first randomly selecting 12 aggregates with a diameter no larger than 6.35 mm, the diameter of the head of a hand-operated pocket penetrometer. On a hard surface, each aggregate was oriented so that the direction of the applied force fell within the base of the aggregate. Using the pocket penetrometer, pressure was applied, perpendicular to the hard surface, until the aggregate failed. The measurement was then repeated for all aggregates. Before the aggregate strength data were summarized for each sample, the highest and lowest readings were dropped because of the variability in strength from aggregate to aggregate.

Aggregate stability was determined using the procedure given by Russell and Feng (1947) modified to wet the aggregates under 4-cm tension (Rhoton et al., 1982). The hydrometer method (Day, 1965) was used to determine the content of sand (*SA*), silt (*SI*), and clay (*CL*) while a method given by Peech et al. (1947) was used to determine the soil organic matter content (*OM*). Immediately before and immediately after each cultivation, additional soil surface samples were taken of gravimetric water content (at cultivation) (*WCCULT*) and bulk density (both dry and wet, *BDD* and *BDW*) using the core method.

When cultivation occurred, plots of Replications II and IV were covered with plastic to exclude natural rainfall. The coverings, though necessary, did serve to increase soil temperatures in the covered plots. To what degree this increase in temperature affected the decomposition of organic matter or aggregate stability in the affected plots is not known. When the time came for those plots to be cultivated, the coverings were carefully removed and the plots cultivated. The effectiveness of the coverings was verified by subsequent water content measurements taken at the soil surface that differed little among planting dates within cultivations.

Elevation measurements

Soil surface elevations were measured after each cultivation using an automated, non-contact profiler (Römkens et al., 1986). The procedure of Römkens and Wang (1986) as modified by Lehrsch (1985) was used. Briefly, after a plot was cultivated, the soya beans growing in a representative 1×1 m subplot were clipped at the soil surface and removed from the subplot. The profiler was then placed over the subplot and leveled. Roughness as surface elevations was subsequently measured as the movable carriage of the profiler traversed the subplot along predetermined transects, separated by 5 cm.

Statistical analyses

The profiler data were analyzed (Römkens et al., 1986; Römkens and Wang, 1986) to obtain estimates of the surface roughness in terms of the *MIF* parameter, Eqn. (2). A reference datum for each transect was established using least-squares regression techniques to fit a line through all measured elevations along the transect. The parameters of Eqn. (2) were then calculated for each of the 21 transects of each plot. Upon examination, the frequency distributions of the *MIF* parameters were found to resemble log-normal distributions. Since the roughness parameters were to be normally distributed for a subsequent analysis of variance, common logarithms of the *MIF* parameters (*LMIF*) were calculated. They were then subjected to a semi-variogram analysis (Clark, 1979) to identify spatial dependency, if present, in the *LMIF* values for the 21 transects of each plot. When dependency was found on a particular plot, only independent transects (i.e., transects separated by distances equal to or greater than the range of that plot's semi-variogram) were used (Lehrsch, 1985) to obtain a mean *LMIF* for the plot.

After estimates of the roughness were obtained, and the soil properties were determined, the data were analyzed statistically. Scatter diagrams were constructed and correlation coefficients were computed (SAS Institute Inc.[1], 1982a) relating the soil properties at the surface or at the 10.8-cm depth and the *LMIF* parameter. In the analyses, the number of independent transects (Lehrsch, 1985) that were used in determining the *LMIF* parameter's value were used in an informal sense to weight the *LMIF* parameter. Soil properties that each explained 2% or more of the variation in *LMIF* were identified and compared to the soil properties identified by other researchers as being important. A forward-stepping, multiple linear regression algorithm (SAS Institute Inc.[1], 1982b) was then used to obtain a statistical relationship between soil surface roughness and the selected soil physical properties.

RESULTS

Surface roughness

After each cultivation, soil surface roughness was measured. Table I gives the measured roughness as the common log of the *MIF* parameter (*LMIF*). The computed *LMIF* values varied somewhat from replication to replication within each treatment. Because the *LMIF* parameter was spatially dependent

[1]See footnote on p. 200.

TABLE I

Soil surface roughness measured at each cultivation

Treatment No.	*LMIF*[1] for each replication				Mean	SD
	1	2	3	4		
1	−0.679	−0.846[2]	−0.748	−0.765	−0.760	0.069
2	−0.801	−0.789	−0.708	−0.854	−0.788	0.060
3	−0.821	−0.806	−0.714[2]	−0.689[2]	−0.758	0.066

[1]The value for each replication is the mean of the *LMIF* parameters measured on either 20 or 21 transects, unless otherwise indicated.
[2]This value is the mean of the *LMIF* parameters measured on not less than 4 or more than 7 transects.

(Lehrsch, 1985) on Treatment 1, Replicate 2, and Treatment 3, Replicates 3 and 4, the *LMIF* values for those three plots were calculated using data from only one-third as many transects as for the remaining plots. Those 3 *LMIF* values also tended to vary somewhat from the *LMIF* values of the remaining replications of their respective treatments.

Soil properties

A number of soil properties from the Ap2 horizon (sampled at the 10.8-cm depth) and the B horizon (sampled at the 30.5-cm depth) were measured. The water content at −33 kPa or one third bar (*WCTH*), aggregate stability, and aggregate size distributions are given in Table II. A relatively wide range in *WCTH* can be seen. However, for every treatment, the Ap2 horizon held less water than the B horizon. Aggregate stability is reported in terms of an initial stability (*INSTA*) and a rate of disintegration (*DIS*) (Russell and Feng, 1947). *INSTA* was an estimate of the stability of aggregates prior to any wet sieving while *DIS* was a measure of the rate at which aggregates disintegrated during wet sieving.

Table II also gives aggregate size distributions in terms of a mean weight diameter, *MWDD* for dry sieving and *MWDW* for wet sieving (van Bavel, 1949; Youker and McGuinness, 1957). As expected, the measure of the mean aggregate diameter reveals larger mean diameters deeper in the soil profile. Somewhat unexpected was the fact that some of the wet diameters were larger than the corresponding dry diameters. The Ap2 horizons of Treatments 1 and 3, and the B horizon of Treatment 1, have larger wet diameters than dry. This suggests that those soil samples disintegrated less during wet sieving than during dry sieving. A number of factors may have been responsible for this finding. First, the soil samples that contained aggregates more resistant to breakdown in a wet environment than in a dry environment tended to be higher in organic

TABLE II

Water content at a matric potential of −33 kPa, aggregate stability, and aggregate size distributions as given by the mean weight diameter

Treatment No.	Soil depth (cm)	Water content at −33 kPa[1] (kg kg^{-1})	Aggregate stability		Mean weight diameter[2,3]	
			Initial stability[2]	Rate of disintegration[2]	Via dry sieving[4] (mm)	Via wet sieving (mm)
1	10.8	0.269	0.694	−0.101	2.08	2.18
1	30.5	0.335	0.696	−0.080	2.45	2.52
2	10.8	0.231	0.701	−0.088	2.25	2.20
2	30.5	0.284	0.693	−0.080	2.43	2.26
3	10.8	0.205	0.682	−0.092	1.80	1.89
3	30.5	0.237[5]	0.701	−0.069	2.66	2.22

[1]Each value is the arithmetic mean of 4 replications, unless otherwise indicated.
[2]Each value is the arithmetic mean of 8 measurements (2 measurements on each of 4 replications).
[3]The Mean Weight Diameter (*MWD*) was defined as the sum of the products of the mean diameter $\bar{x}_i$ and the proportion W_i of the total sample weight of each size fraction according to the relationship $MWD = \sum_{i=1}^{n} \bar{x}_i W_i$.
[4]The aggregates at the time of dry sieving were at their air-dry water content (0.034 kg kg^{-1}).
[5]Mean of 3 replications.

matter (2.06% or more, Table III). Second, the movement of the sieves was less vigorous in the wet-sieving procedure than in the dry-sieving procedure. Third, during the wet sieving, water movement through the nest of sieves was

TABLE III

Soil organic matter content and mechanical analysis

Treatment No.	Soil depth (cm)	Organic matter content[1] (%)	Sand (%)	Silt (%)	Clay (%)	Textural class[2]
1	10.8	2.16	21.0[1]	46.5	32.5	Clay loam
1	30.5	2.14	20.9	44.3	34.8	Clay loam
2	10.8	2.05	27.3	44.5	28.2	Clay loam
2	30.5	1.91	28.1	43.3	28.6	Clay loam
3	10.8	2.06	30.4	41.0	28.6	Clay loam
3	30.5	1.92	29.5	40.8	29.7	Clay loam

[1]Each percentage represents the arithmetic mean of 8 measurements (2 measurements on each of 4 replications).
[2]The USDA scheme (Soil Survey Manual, 1951) was used to determine the textural class.

TABLE IV

Soil conditions before each cultivation (each treatment)

Soil property	Replication				Mean
	1	2	3	4	
Treatment 1					
Water content ($kg\,kg^{-1}$)	0.047	0.083	0.055	0.055	0.060
Dry bulk density ($Mg\,m^{-3}$)	1.07	1.07	1.02	1.03	1.05
Wet bulk density ($Mg\,m^{-3}$)	1.12	1.15	1.07	1.08	1.10
Treatment 2					
Water content ($kg\,kg^{-1}$)	0.140	0.089	0.150	0.102	0.120
Dry bulk density ($Mg\,m^{-3}$)	1.15	1.11	1.03	1.21	1.12
Wet bulk density ($Mg\,m^{-3}$)	1.32	1.21	1.18	1.33	1.26
Treatment 3					
Water content ($kg\,kg^{-1}$)	0.206	0.206	0.216	0.202	0.208
Dry bulk density ($Mg\,m^{-3}$)	1.23	1.15	1.27	1.38	1.26
Wet bulk density ($Mg\,m^{-3}$)	1.48	1.39	1.55	1.66	1.52

not vigorous, because flow through the nest was hindered by the relatively small openings (0.25 mm) in the lowermost sieve. Fourth, dry sieving was conducted for 10 min, whereas wet sieving was conducted for only 8 min.

The *OM* of the soil in the study area was consistently greater in the Ap2 horizon than in the B horizon (Table III). Also, the texture of the soil reveals a consistent increase in clay content with depth.

Soil structure, determined in the field, was most often moderate and strong fine and medium angular blocky or, less frequently, weak and moderate fine and medium subangular blocky for the Ap2 horizon. In three plots, Treatment 1, Replication 2 and Treatment 3, Replications 2 and 4, two types of structure were noted; one being weak medium granular and the other being weak fine and medium angular blocky. The soil structure of the B horizons was either weak fine and medium blocky or weak fine and medium subangular blocky, with each occurring as often as the other.

The soil properties measured at the soil surface before the first, second, and third cultivations (Table IV) showed, for each measured parameter, relatively good agreement among replications within cultivations. Also, from the first to the third cultivation (that is, from Treatment 1 to Treatment 3) there is a consistent increase in water content and bulk density. Using this data, surface roughness can be related to a relatively large range (over a 3-fold difference) of values of the gravimetric water content at the time of cultivation (*WCCULT*). The bulk density increase was surprising, since previous cultivations should have decreased the bulk density at the soil surface. However, throughout the experiment, the sweeps of the cultivator owing to equipment

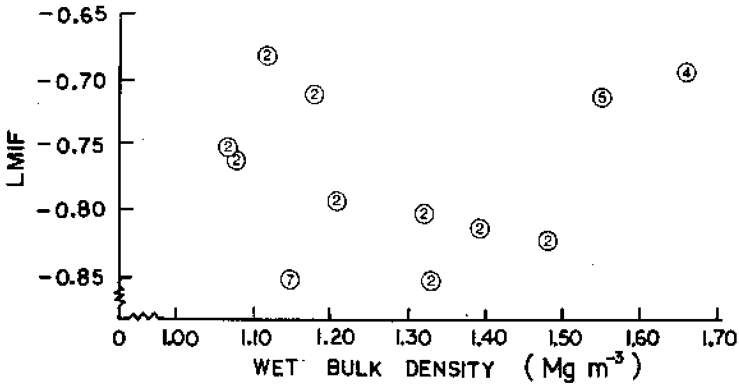

Fig. 3. Scatter diagram of *LMIF* versus wet bulk density.

limitations tended to travel on the soil surface, rather than penetrating into the profile. In doing so, the sweeps compacted the surface horizon, thereby increasing its bulk density.

DISCUSSION

Simple correlations

In relating the soil surface roughness to the soil physical properties of the plots on which the roughness was measured, simple correlation coefficients were first determined between *LMIF* (so as to use a normally distributed roughness parameter) and the soil physical properties measured at the soil surface prior to each cultivation and at the 10.8-cm depth prior to primary tillage. *WCCULT* and bulk density, shown by other researchers (Allmaras et al., 1967; Lyles and Woodruff, 1961) to be related to soil surface roughness, were found each to account for less than 1% of the variation in *LMIF*. This finding differed from established relationships, and warranted further investigation.

Scatter diagrams of the *LMIF* parameter versus each soil property were constructed. Each point in the scatter diagrams was coded using the number of transects used to calculate that plot's *LMIF* parameter (Lehrsch, 1985). A scatter diagram for *BDW* is shown in Fig. 3. The points in the scatter diagram plotted as a 4, 5, or 7 correspond to those plots on which the *LMIF* parameter was calculated (owing to spatial dependency) using only 4, 5, or 7 transects, while the points plotted as a 2 correspond to those plots on which the *LMIF* parameter was calculated using 20 or 21 transects. It is apparent that those points which represent fewer transects are not following the pattern set by the remaining points. The scatter diagrams for the remaining soil physical properties also indicated those 3 points to be outliers.

Data from these 3 plots were therefore eliminated from further consideration, and a correlation analysis was performed a second time. In Table V are listed the soil physical properties that individually accounted for 2% or more of the variation ($R^2 \geq 0.02$) in the *LMIF* parameter. Dry bulk density alone accounted for the most variation in *LMIF*, explaining 64% (the square of the correlation coefficient of -0.80 from Table V), while wet bulk density individually explained 52% of the variation in *LMIF*. Other important soil properties included (1) *WCTH* and (2) *WCCULT*.

As the bulk density increased, the roughness decreased (Table V and Fig. 3). Over the growing season, as more and more cultivations took place, the soil at the plot surface became more and more compacted (Table IV). With the increase in bulk density, there was an attendant decrease in porosity. Such a decrease in porosity suggests that aggregates that had been situated on the soil surface had been destroyed by the sweeps of the cultivator and that the soil particles from the disintegrated aggregates were now occupying the soil pore space. The displacement of aggregates or clods from the soil surface would tend to lower (1) the peak frequency, *FREQ*, (2) the microrelief index, *MI*, and (3) the product of the two, the *MIF* parameter. However, the inverse relationship between bulk density and roughness disagrees with the results of Lyles and Woodruff (1961), who found an increase in the cloddiness of surface soil with an increase in bulk density. The discrepancy is attributed to the use of different experimental procedures. In the study of Lyles and Woodruff (1961), a chisel that was mechanically drawn through compacted soil decreased the bulk density at the soil surface, whereas in this study cultivator sweeps drawn over the surface of tilled plots compacted the surface soil, increasing its bulk density (Table IV). In any case, the influence of bulk density on soil surface roughness is clearly evident.

WCTH was directly proportional to soil surface roughness (Table V). The correlation matrix of soil surface roughness and the most important soil properties shows that *WCTH* was directly proportional to both *SI* and *OM*, as was also found by Allmaras et al. (1967) and noted by Baver et al. (1972). Thus, all 3 factors, *WCTH*, *SI*, and *OM*, act to increase soil surface roughness as they themselves increase. From the data presented by Allmaras et al. (1967), there is also some indication that, across two of the 3 soil associations they studied, soil surface roughness is directly related to the water content at the lower plastic limit (estimated by *WCTH*), as Table V also indicates. Allmaras et al. (1967) also observed that clay content did not always affect random roughness. This study seems to confirm their observation, since *CL* accounted for less than 2% of the variation in the *LMIF* parameter.

As *WCCULT* decreases, soil surface roughness increases (Table V). In this study, cultivations were performed when the water content of the soil surface was less than the water content at the lower plastic limit. Hence, the results of

TABLE V

The correlation matrix of soil surface roughness and the soil properties each accounting for two percent or more of the variation in surface roughness

Soil property	Soil property									
	LMIF	*BDD*	*BDW*	*WCTH*	*WCCULT*	*SI*	*SA*	*MWDD*	*OM*	*DIS*
Log of *MIF* (*LMIF*)	1.00									
Dry bulk density (*BDD*)	−0.80	1.00								
Wet bulk density (*BDW*)	−0.72	0.92	1.00							
Water content at $\psi = -33$ kPa (*WCTH*)	0.48	−0.57	−0.76	1.00						
Water content at cultivation (*WCCULT*)	−0.46	0.62	0.87	−0.85	1.00					
Silt content (*SI*)	0.43	−0.50	−0.63	0.47	−0.68	1.00				
Sand content (*SA*)	−0.40	0.65	0.82	−0.81	0.86	−0.62	1.00			
Mean weight diam. — dry sieving (*MWDD*)	−0.32	−0.00	−0.27	0.28	−0.51	−0.06	−0.38	1.00		
Organic matter content (*OM*)	0.19	−0.03	−0.07	0.28	−0.17	0.46	−0.19	−0.39	1.00	
Rate of disintegration (*DIS*)	−0.16	0.31	0.14	0.10	−0.09	−0.50	−0.01	0.54	−0.43	1.00

this study support the findings of Allmaras et al. (1967) that surface roughness increased as water contents below the lower plastic limit decreased.

Regression equation

The 9 soil physical properties listed in Table V were subsequently used in a forward-stepping, multiple linear regression analysis to obtain an equation describing soil surface roughness. The best equation was

$$LMIF = -0.0501 - 0.0924\ (MWDD) - 0.3830\ (BDW) + 0.6097\ (DIS) \qquad (3)$$

where *LMIF* is the plot average of the common logarithm of the *MIF* parameter of Eqn. (2), *MWDD* is the mean weight diameter of aggregates in the Ap2 horizon, *BDW* is the wet bulk density measured at the soil surface prior to cultivation, and *DIS* is the rate of disintegration of the aggregates in the Ap2 horizon. Eqn. (3) describes over 91% of the variation in *LMIF* and has relatively low correlation (<0.55) among its independent variables. From Eqn. (3), a decrease in *MWDD*, an increase in *DIS*, or both, result in a rougher soil surface after cultivation. No explanation for such a relationship is apparent. Eqn. (3) also indicates that an increase in *BDW* results in a decrease in soil surface roughness, just as was noted and discussed above.

The findings of this study have implications for further research. Bulk density and, to a lesser degree, water content and soil texture are the soil physical properties that should be studied in greater detail, in order to identify the specific mechanisms whereby they affect the microrelief of the soil surface after tillage or cultivation. The further study of aggregates (their distributions as indicated by a mean weight diameter, and their resistance to breakdown as indicated by organic matter content and rate of disintegration) might also prove fruitful in relation to their effect upon soil surface roughness.

CONCLUSIONS

If a relationship is desired between surface roughness and a single soil property, bulk density shows the most potential. Dry and wet bulk density, measured at the soil surface prior to cultivation, accounted for the most variation in soil surface roughness, explaining 64 and 52%, respectively (the squares of the respective correlation coefficients of Table V). Water content or soil texture also show potential. Water content at cultivation, and at a matric potential of -33 kPa, accounted for 21.0 and 22.9% of the variation in soil surface roughness, respectively. Other soil physical properties, especially soil texture, also affected the roughness of the soil surface after cultivation, but to a lesser degree.

On the other hand, if a relationship is desired between soil surface roughness and some combination of soil properties, the most promising properties are mean weight diameter, bulk density, and the rate of aggregate disintegration. The mean weight diameter and rate of disintegration of aggregates in the Ap2 horizon along with the wet bulk density of the soil surface explained over 91% of the variation in soil surface roughness measured after cultivation.

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