Infiltration as Influenced by Tillage-Induced Random Roughness and Pore Space[1]

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ABSTRACT

During simulated rainfall, increases in tillage-induced random roughness and pore space increased water infiltration before runoff started but did not significantly influence infiltration throughout a 5-cm runoff period. Random roughness provided a greater accounting of infiltration variation among tillage treatments to initial runoff than did total pore volume of the tilled layer.

Freshly turnplowed alfalfa-bromegrass sod on Barnes loam and Nicollet sandy clay loam soil provided random roughness and pore space conditions that could accommodate without "failure" the major portion of rainfall energy (as evidenced by EI) expected in west central and southwestern Minnesota during the first 2 months following row crop planting. This is the critical runoff-erosion period in the Corn Belt.

Additional Key Words for Indexing: water intake, tillage, rainfall erosion index (EI), runoff.

TILLED SOIL surface conditions favorable for rapid infiltration of water are needed in regions where water conservation and erosion control are major problems. Recognizing the need for better physical description of soil conditions that meet this need, Larson (7) suggested soil parameters for tillage evaluation. Techniques for measuring roughness and total pore space of tilled soil surfaces have been described (1, 4), and the effects of tillage and rainfall on the soil surface structure and subsequent infiltration characteristics of Barnes loam have been reported by Burwell et al. (5). The techniques used in these studies provide a framework upon which to evaluate tillage for runoff-erosion control.

To describe soil management practices that will enhance infiltration, we need three general types of information. First, we need an understanding of the physical response of various soils to different tillage operations. Soil type, water content and pore space at time of tillage, and cropping prior to tillage affect the physical condition of soil surfaces created by a given tillage operation (1, 2). Second, we need to know how described tillage-induced soil physical conditions respond to the accumulated impact of rainfall energy. Third, we need information on the seasonal distribution of average annual rainfall energy. Wischmeier and Smith (9) have established a Rainfall Erosion Index (EI), which is computed as the product of the total kinetic energy of the storm and its maximum 30-min intensity.

The study reported here was conducted on two soils to ascertain the influence of tillage-induced soil-surface condition on rainfall infiltration. The soil-surface conditions are evaluated on the basis of the rainfall energy required to initiate runoff on a freshly tilled bare soil surface. Also included is a description of how available EI data can be used in combination with these tillage-infiltration research results to establish criteria for selecting tillage practices for erosion control.

PROCEDURE

Tillage studies were conducted in 1965 on Barnes loam near Morris, Minn., and on Nicollet sandy clay loam near Lamberton, Minn. The plot sites were on a 4.5% slope and had been in alfalfa-bromegrass for several years.

Tillage treatments were selected that provided large or small total pore volumes within the tilled layer in combination with various magnitudes of surface random roughness. Five tillage treatments were replicated three times on each soil. The tillage treatments were: (i) untilled for at least 3 years, (ii) moldboard turnplowed to a depth of 15 cm, (iii) moldboard turnplowed to a depth of 15 cm, tandem disked, and spike-tooth harrowed, (iv) rotary tilled to a depth of 15 cm, and (v) cultivated with a field cultivator equipped with chisel points operated to a depth of 7.5 to 10 cm on untilled soil. Surface crop residues were removed before tillage for all treatments. Tillage operations were in an up-slope direction. Implement wheel traffic over the plot area was avoided after tillage. A 100- by 100-cm area, centered in the plot was used for measuring random roughness, total porosity, and infiltration. This area was covered after tillage to protect it from natural rainfall.

Methods for measuring porosity and random roughness are described by Burwell et al. (4) and Allmaras et al. (1). Briefly, the sampling technique requires undisturbed core sampling before tillage and surface height measurements before and after tillage. These measurements were used in combination with each other to determine the total pore space for the 0- to 15-cm surface layer and the random roughness of the soil surface. The surface height measurements, obtained with a point quadrate device (microrelief meter), were measured to the nearest 0.25 cm on a 5- by 5-cm grid for a 100- by 100-cm area centered in the plot. Total pore space after tillage was computed as the sum of total pore space before tillage and the vertical volume change in space as determined from the average of 400 height measurements made on the surface before and after tillage. Random roughness was computed as the average standard error among the 400 height measurements.

A sprinkler-type infiltrometer similar to that described by Bertrand and Parr (3) was used to apply artificial rainfall at the rate of 12.7 cm/hour until 5 cm of runoff occurred. Pore space and random roughness measurements were made before water application, at initial runoff, and after 5 cm of runoff. A Veejet (80100) nozzle described by Meyer and McCune (8) was used on the infiltrometer unit. (Mention of commercially manufactured equipment does not imply endorsement by the USDA over similar equipment not mentioned.) The nozzle provided an oscillating motion across the plot. The drop size distribution and average fall velocities were similar to those described by Meyer and McCune (8). The kinetic energy of the resulting simulated rain was approximately 22 metric-ton meters per hectare millimeter of rain or approximately 71% of the kinetic energy of natural rainfall at an intensity of 12.7 cm per hour. A knowledge of the relationship between simulated rainfall and natural rainfall permits tillage systems to be evaluated as runoff and erosion control practices.

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RESULTS AND DISCUSSION

Tillage-Induced Surface Conditions

Significant differences in random roughness and total pore space of the 0- to 15-cm surface layer were obtained with the various tillage treatments within each soil type (Table 1). Moldboard plowing produced the highest random roughness and pore space on both the Barnes and the Nicollet soils. For both soils, the second highest random roughness was obtained with the cultivator, and the second highest pore space was obtained with the rotary tiller. On both soils, random roughness and pore space were lowest for the untilled treatment.

Rainfall Alteration of Surface Conditions

Much of the random roughness and total pore space created by tillage was decreased by the time runoff began (Table 1). However, differences among tillage treatments remained after 5 cm of runoff.

By the time runoff began on the Barnes soil, random roughness had significantly decreased only on the plowed treatment, and pore space had significantly decreased on both the plowed and cultivated treatments (Table 1). Random roughness did not change significantly during the 5-cm runoff period for any of the tillage treatments on the Barnes soil. Pore space significantly decreased during the runoff period for the rotary tilled treatment only.

On the Nicollet soil, random roughness significantly decreased on all tilled treatments both during the period to initial runoff and during 5 cm of runoff. Rainfall applied to initial runoff significantly decreased pore space for all except the cultivated treatment, but there was no significant change for any treatment during the 5-cm runoff period.

Infiltration and Rainfall Energy Required to Initiate Runoff

Cumulative infiltration and rainfall energy required to initiate runoff were greater on the rough, porous surface created by the plow treatment than for any of the other tillage treatments (Table 2). The total infiltration and rainfall energy required during the 5-cm runoff period for each soil did not differ significantly among tillage treatments, even though significant differences in random roughness and total pore space existed throughout this period. This suggests that the hydraulic conductivity through the overall plot surfaces (100- × 100-cm area) was restricted by surface seals. Continuous surface seals were visually observed on all treatments by the time runoff started. Thus, the influence of tillage-induced random roughness and pore space on infiltration during the runoff period was overshadowed by the surface seal induced by the cumulative rainfall action to initial runoff.

Water intake to initial runoff and from initial to 5 cm of runoff were each estimated as a function of random roughness and total pore space existing at the beginning of these respective periods (Fig. 1). In Table 3, multiple regression analysis (Columns 2, 3, and 4) and Venn Diagram Analysis (Columns 5, 6, and 7) were used to further understand the influence of random roughness and pore space on infiltration. The multiple regression analysis did not mathematically adjust for the physical influence of the unspecified parameter. The Venn Diagram analysis mathematically adjusted for the physical influence of the unspecified parameter. Prior to initial runoff, differences in tillage-induced random roughness accounted for most of the variation in infiltration, whereas differences in total pore space, considered alone or in combination with random roughness, caused only minor variations in infiltration (Table 3). In contrast, the water intake during the 5-cm runoff period was little affected by the two variables considered jointly or independently. The low accounting of water intake during the 5-cm runoff period for the two soils (Fig. 1) contrasts to the consistent and significantly higher accounting obtained during the period prior to runoff initiation. For both soils, the independent infiltration accounting to initial runoff rendered by random roughness (Column 5, Table 3) was at least 11-fold greater than that rendered by independent total pore space (Column 6, Table 3). The large accounting by random roughness and total pore space in common (Column 7, Table 3) indicated a significant interaction effect of these parameters on infiltration.

In the response surface diagram shown in Figure 1, there is a nonuniform scatter of coordinate points (as identified by the average value obtained for each of the tillage treatments) for each soil in the random roughness—total pore space base plane. This scatter reflects the inability to create a surface soil structure condition of low total pore space in combination with high random roughness. Thus, considerable joint variation in random roughness and total pore space occurred in the treatments (Column 8, Table 3). Therefore, it was not possible to completely separate the physical influence of random roughness from total pore space on infiltration.

Table 1—Effect of tillage and artificial rainfall on random roughness and total pore space*

Soil type	Tillage treatment	Before tillage	After tillage	At initial runoff	After 5 cm of runoff
		Random Roughness, cm			
Barnes loam	Untilled	0.6 a†	0.6 a	0.6 a	0.5 a
	Plowed	.5 a	5.7 h	4.3 g	3.8 gf
	Plowed-disked-harrowed	.8 ab	1.5 bc	1.2 bc	1.0 bc
	Cultivated	.5 a	3.4 f	3.1 ef	2.6 de
	Rotary tilled	.6 a	1.7 c	1.4 bc	1.2 bc
		Total Pore Space, cm			
Barnes loam	Untilled	8.0 a	8.0 a	8.0 a	8.1 a
	Plowed	8.3 a	13.9 j	12.6 hi	12.1 gh
	Plowed-disked-harrowed	8.0 a	10.6 cd	10.2 bc	9.8 b
	Cultivated	8.4 a	11.3 ef	10.7 cd	10.4 cd
	Rotary tilled	8.1 a	12.9 i	11.8 fg	10.9 de
		Random Roughness, cm			
Nicollet sandy clay loam	Untilled	0.5 a	0.5 a	0.5 a	0.5 a
	Plowed	0.5 a	4.6 j	3.7 i	3.1 h
	Plowed-disked-harrowed	0.5 a	1.5 f	1.2 d	1.0 b
	Cultivated	0.5 a	1.6 g	1.3 e	1.2 d
	Rotary tilled	0.4 a	1.3 e	1.1 c	.9 b
		Total Pore Space, cm			
Nicollet sandy clay loam	Untilled	7.1 a	7.1 a	7.1 a	7.8 b
	Plowed	7.2 a	14.1 i	13.0 gh	13.0 gh
	Plowed-disked-harrowed	7.3 a	12.6 fg	12.3 de	12.1 d
	Cultivated	7.2 a	8.2 c	8.2 c	8.3 c
	Rotary tilled	7.1 a	12.9 g	12.4 ef	12.2 de

* Rainfall applied at the rate of 12.7 cm/hour.
† Values not followed by the same letter are significantly ($p = 0.05$) different among tillage treatments and times within a soil type and soil structure parameter as determined by the Duncan Multiple Range Test.

Table 2—Effect of tillage on cumulative infiltration and rainfall energy required to initiate runoff on a Barnes loam and a Nicollet sandy clay loam*

Tillage treatment	Surface condition after tillage: Pore space	Random roughness	Rainfall kinetic energy: To initial runoff	During 5-cm runoff	Cumulative infiltration: To initial runoff	During 5-cm runoff
	cm	cm	M ton-m/ha-mm†		cm	cm
Barnes Loam						
Untilled	8.0‡	0.6‡	8.1 a§	18.2 a	0.9 a	2.1 a
Plowed	13.9	5.7	80.4 c	18.2 a	9.3 c	2.1 a
Plowed-disked-harrowed	10.6	1.5	21.0 a	18.2 a	2.4 a	2.1 a
Cultivated	11.3	3.5	57.4 b	20.2 a	6.7 b	2.4 a
Rotary tilled	12.9	1.7	41.4 b	18.0 a	4.8 b	2.1 a
Nicollet Sandy Clay Loam						
Untilled	7.1	0.5	8.1 a	39.4 a	0.9 a	4.6 a
Plowed	14.1	4.6	136.7 d	49.1 a	15.8 d	5.7 a
Plowed-disked-harrowed	12.6	1.5	44.0 b	45.8 a	5.1 b	5.3 a
Cultivated	8.2	1.6	64.2 c	37.5 a	7.4 c	4.3 a
Rotary tilled	12.9	1.3	42.9 b	36.1 a	5.0 b	4.2 a

* Rainfall applied at the rate of 12.7 cm/hour.
† Metric-ton meters per hectare millimeter of rain. To convert to EI multiply the table values by 0.37.
‡ Data obtained from Table 1 after tillage eolumn.
§ Values not followed by the same letter within a column and soil type are significantly ($p = 0.05$) different as evaluated by the Dunean Multiple Range Test.

Table 3—Variation in water intake accountable by random roughness and total pore space—both alone and in combination

Soil type	R and P both specified	R with P unspecified	P with R unspecified	R independent of P	P independent of R	R and P in common	Joint variation of roughness and pore space†
	Percent of water intake variation accounted for by specified conditions on random roughness (R) and total pore space (P)*						
	Water Intake to Initial Runoff						After tillage
Barnes loam	87.4	85.0	59.3	28.1	2.4	56.9	47.2
Nicollet sandy clay loam	97.8	93.3	42.5	55.3	4.4	38.0	31.7
	Initial to 5 cm Runoff						At initial runoff
Barnes loam	15.9	0.4	6.7	9.2	15.5	-8.8	48.5
Nieollet sandy clay loam	29.5	27.5	5.4	23.7	1.4	4.7	21.3

* Columns 2, 3, and 4 were obtained from the respective multiple regression models:

$$Y = \alpha_1 + \beta_1 P + \beta_1' P^2 + \beta_1 R + \beta_1' R^2,$$

$$Y = \alpha_2 + \beta_2 R + \beta_1' R^2 \text{ and } Y = \alpha_3 + \beta_3 P + \beta_3' P^2$$

where Y is water intake, R is the random roughness, P is the total pore space, and the α's and β's are parameters. Columns 5, 6, and 7 were determined by Venn Diagram analysis which mathematically adjusted for the physical influence of the unspecified parameter. † $r^2 \times 10^2$, where r is the simple correlation between random roughness and total pore space.

Tillage for Runoff-erosion Control

This study shows that freshly tilled, rough, porous surfaces offer considerable more opportunity for infiltration than smoother surfaces characteristic of conventional tillage practices for row crops (Table 2). Free (6) suggested that the objective of soil management should be to create soil conditions to meet without "failure" the stress design of rainstorms. Moldenhauer and Burwell (W. Moldenhauer and R. E. Burwell. 1966. Influence of maximum clod size on energy required to initiate runoff. *Unpublished manuscript. Agron. Abstr. p. 93*) defined the point of "failure" as that point at which runoff is initiated. The cumulative impact of rainfall energy on freshly tilled soils usually alters the surface. Thus, the described physical condition of tilled soil surfaces and the cumulative rainfall energy occurring after tillage should be jointly considered in evaluating tillage practices.

To apply the results reported here to field situations, we need information on seasonal distribution of average annual kinetic energy occurring from natural rainfall. This information is not presently available. However, Wischmeier and Smith (9) have used EI to characterize the

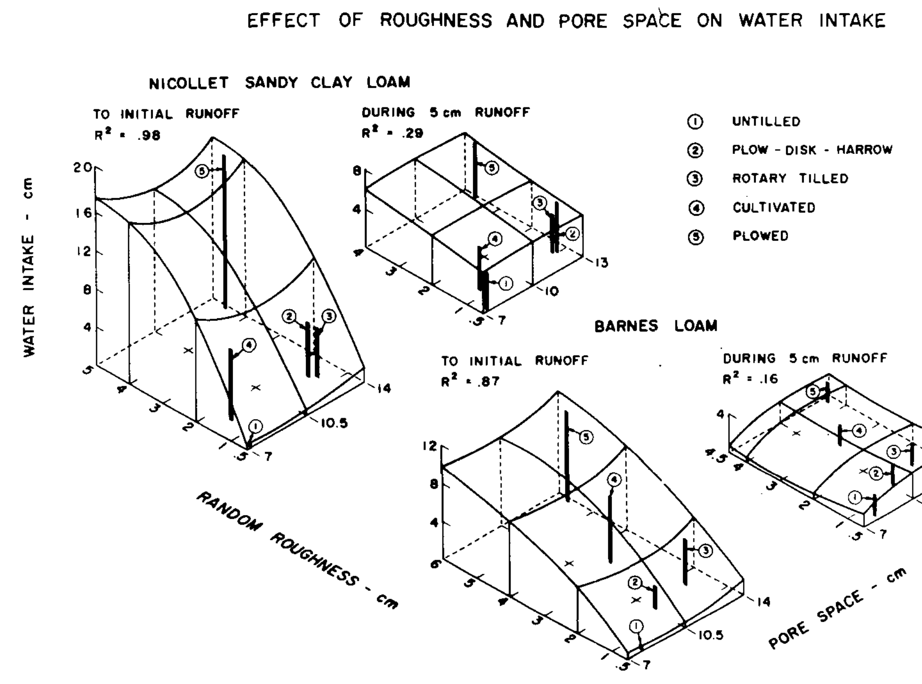

Fig. 1—Influence of tillage on soil structure (random roughness and total pore space) and subsequent water intake.

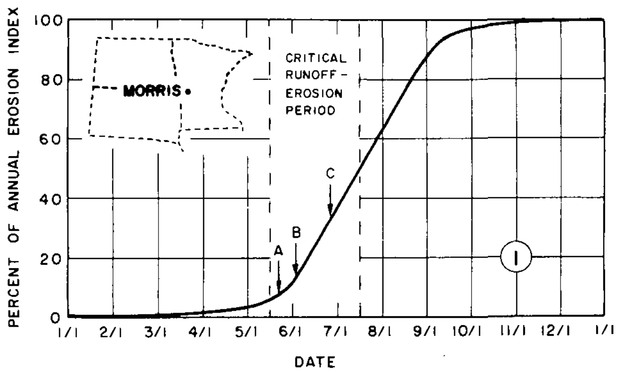

Fig. 2—Points of "failure" for three surface roughness conditions on Barnes loam soil following tillage of alfalfa-bromegrass sod. (EI distribution curve for northern Minnesota obtained from Wischmeier and Smith (9).) Points of failure for bare surface conditions identified as follows: *A* = untilled, *B* = plowed-disked-harrowed, *C* = plowed. Respective random roughness are 0.5 cm, 1.5 cm, and 5.8 cm.

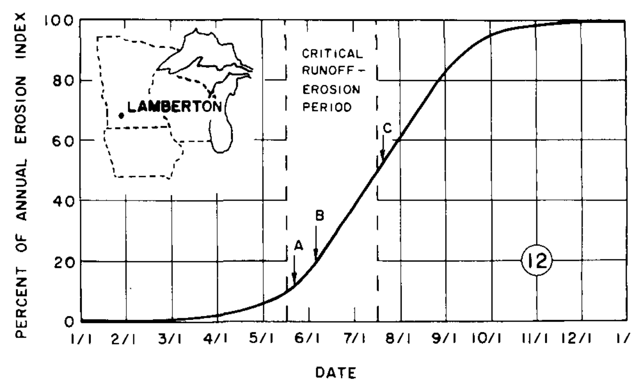

Fig. 3—Points of "failure" for three surface roughness conditions on Nicollet sandy clay loam soil following tillage of alfalfa-bromegrass sod. (EI distribution curve for southern Minnesota obtained from Wischmeier and Smith (9).) Points of failure for bare surface conditions identified as follows: *A* = untilled, *B* = plowed-disked-harrowed, *C* = plowed. Respective random roughnesses are 0.5 cm, 1.5 cm, and 4.6 cm.

annual distribution of rainfall erosivity for various cropland areas east of the Rocky Mountains. This parameter is computed as the accumulated sum of the product of the total kinetic energy of each rainstorm and its maximum 30-min intensity. At the Barnes loam experimental site in west-central Minnesota, 42 of the 100 average annual units of EI occur during the critical runoff-erosion period between May 15 and July 15 (Fig. 2). In southwestern Minnesota (Nicollet sandy clay loam site), the average annual EI is 120, of which 50 units occur during the critical runoff-erosion period between May 15 and July 15 (Fig. 3). The EI of the sprinkling infiltrometer used was calculated to be about 71% of the EI of natural rainfall with the same intensity. Thus, for Barnes loam, the surface physical condition induced by turnplowing alfalfa-bromegrass sod at the beginning of the cropping season, would accommodate without "failure" about 71% (multiply 80.4 (Column 4, Table 2) by 0.37 and divide by 42) of the EI normally occurring during the critical erosion period. However, if the surface condition at the beginning of the cropping season was representative of the plow-disk-harrow treatment, only 19% of the expected EI would be accommodated before the point of "failure" occurred. The three points of "failure" for the untilled, plowed-disked-harrowed, and plowed surface treatments are shown on the EI distribution curve (Fig. 2) for the Barnes soil following alfalfa-bromegrass sod. A similar analysis for the Nicollet soil indicates that the points of "failure" for turnplowing and plowing-disking and harrowing alfalfa-bromegrass sod are 100 and 32%, respectively, of the expected EI during the critical erosion period (Fig. 3). Extension of these analyses to other tillage, soil, and cropping situations should provide a basis for selecting tillage practices favorable for infiltration and subsequent runoff-erosion control.

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