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Runoff and sediment losses from rough and smooth soil surfaces in a laboratory experiment

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Abstract

Soil surface roughness may significantly impact runoff and erosion under rainfall. A common perception is that runoff and erosion are decreased as a function of roughness because of surface ponding and increased hydraulic roughness that reduces effective flow shear stress. The objective of this study was to measure the effects of initial surface roughness on runoff and erosion under controlled laboratory conditions. Initially, rough and smooth surfaces were exposed to five simulated rainfall applications at 5% and 20% slopes. In all cases, runoff was delayed for the case of the initially rough surface; however, this effect was temporary. Overall, no statistical differences in either total runoff or erosion were measured on the 20% slope. At 5% slope, runoff was less on the rough surface for the first rainfall application but greater on the final three, probably due to the formation of a depositional seal in that case. This resulted in an overall insignificant difference in runoff for the sum of the five rainfall applications. Erosion was greater on the rougher slope at 5% steepness, probably due to concentration of flow as it moved around the roughness elements on the rougher slope. These results indicate that commonly held perceptions of the impact of soil surface roughness on runoff and erosion may not be entirely correct in all cases.

Keywords: Erosion, Sediment; Runoff; Soil surface roughness; Rainfall simulation; Tillage, Rills

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1. Introduction

Soil surface roughness significantly impacts runoff and sediment generation under rainfall in several different ways. One important effect is the greater infiltration rate of the soil with greater roughness, although this effect tends to disappear due to surface sealing as rainfall progresses (Moore and Singer, 1990). Depressional storage also reduces runoff, and its effect also decreases with cumulative rainfall as the depressional storage areas fill with water and as connectivity of runoff increases (Onstad, 1984). Soil erosion may be lessened under conditions of greater roughness not only from the reduction of runoff but also due to the greater level of hydraulic resistance that dissipates the energy of flow (Einstein and Barbarossa, 1951), making a fraction of the total flow energy unavailable for transport of sediment (Foster, 1982; Abrahams and Parsons, 1991). In addition, erosion is affected by the resistance of soil to detachment by raindrop impact due to the modification of the clod size distribution (Römkens and Wang, 1986; Moldehauer and Kemper, 1969).

All of these effects tend to cause erosion on rough surfaces to be less than that on a correspondent smoother slope. However, these effects are mainly active during the early stages of rainfall and are observable until runoff fills and interconnects the soil depressions, and a complete drainage network is developed. Most of the studies on the effect of the roughness induced by tillage have been concentrated on these early stages of rainfall and have been conducted on small laboratory or field plots. The usual observations reported in the literature and the common manner that models account for roughness effects on erosion indicate that a smooth surface generally yields more runoff and sediment than does a rough one (Zobeck and Onstad, 1987; Renard et al., 1997; Hairsine and Rose, 1992).

When the effect of the initial roughness on runoff and soil losses was studied at a scale large enough for the overland flow to reach a natural velocity, the experimental results have challenged the conventional view previously commented, showing little effect of roughness on runoff and overall higher sediment yield on the rougher surface at steep slopes. Helming et al. (1998) conducted a laboratory experiment using a rainfall simulator and a silt loam soil with three roughness treatments (rough, medium and smooth) and three slope treatments (2%, 8% and 17%). Their results showed that during the initial stages of rainfall, runoff and erosion were delayed on the rougher surfaced soils. However, as the experiment progressed, both runoff and erosion were less affected by the roughness treatments. In the end, the total runoff amounts did not vary as a function of the roughness treatments, and at the two steeper slopes, the total erosion rates were actually greater for the rougher soil surface treatments. Helming et al. (1998) explained this in terms of the surface features that were of the same order of magnitude or larger in size than the flow depth, which affected the spatial distribution of the overland flow (Abrahams and Parsons, 1990) and induced a higher degree of flow concentration on the rough surfaces (Römkens et al., 2001). Toward the end of the Helming et al. experiments (e.g., 135 to 180 mm of rainfall), the smooth surfaces eventually developed incised rills, and in these latter phases, the erosion rates on the smooth surfaces were essentially the same as those for the rough surfaces.

The objective of the current study was to increase our understanding of the effect of different initial soil surface roughness on runoff and sediment yield in the various stages of runoff generation: from the beginning of the rainfall to a time when all the surface depressions have been filled and a network draining the whole flume surface has been established. In part, we wish to test the somewhat controversial results obtained by Helming et al. (1998) for roughness effects on erosion.

2. Materials and methods

2.1. Flume and soil preparation

Experiments were performed in a flume 2 m wide and 4 m long. The four experimental treatments consisted of two different slope steepnesses (20% and 5%) at two different initial surface conditions: low unoriented roughness (hereafter smooth); and large unoriented roughness (hereafter rough). The flume was built with free drainage at the bottom. It consisted of a rectangular box, open at the top and the bottom, surrounding a small sloped soil bed. This slope was formed by a 0.05-m-deep gravel layer, on top of which a sand slope was prepared. The depth of the sand slope varied according to the slope steepness. The minimum sand depth was 0.05 m at the flume outlet. The maximum sand depth at the highest point of the surface was 0.85 and 0.15 m for the 20% and 5% slope, respectively. A layer of topsoil 0.28 m thick was placed on top of the sand.

The soil used was a Camden silt loam (Fine silty, mixed Typic Hapludalf) collected from the Tippecanoe County, Indiana. The natural consolidated soil has a bulk density between 1.3–1.5 g cm^{-3} and an organic matter content between 1% and 2% (Ziegler and Wolf, 1998). All the soil was air dried and sieved through a 2-mm screen to insure homogeneity. The soil was placed in successive layers of 0.06 m thickness except the final top layer of 0.04 m. The procedure to place each soil layer was as follows. First, the receiving surface was slightly raked, and the soil was spread. After homogeneously distributing the soil with hands and rakes, it was slightly packed using a 5-kg weight with an approximate surface area of 225 cm^2. The surface was covered with a geotextile material (to prevent surface sealing), and 30 mm of rainfall was applied for approximately 3 h. The geotextile material was removed, and the cracks and depressions observed on the surface 72 h after the rain were filled with more dry soil, and the surface was reshaped. We waited 5 days after reshaping the surface before placing a new soil layer, and the same steps were repeated until reaching the level of the flume outlet that remained at a constant level throughout the whole experiment. This situation, i.e., no base level change, is that which has been used in most of the runoff plots used in previous rill and erosion experiments although experiments with variable base level have been reported (e.g., see Parker, 1977). We changed the slope steepness by modifying the profile of the sand base.

The smooth surface was the first surface to be prepared for each set of replications. The procedure described in the previous paragraph ensured a smooth surface. The rough treatment was prepared by simulating tillage on the surface using a hand hoe (the blade 0.15 m wide and 0.1 m long) creating a rough, nonoriented surface. We chose those treatments to create two different surface situations that were possible to replicate. Fig. 1 shows examples of the initial surfaces.

The following procedure was adopted to perform tillage under similar conditions of soil moisture and density. After the experiment on the smooth surface was finished, we let the

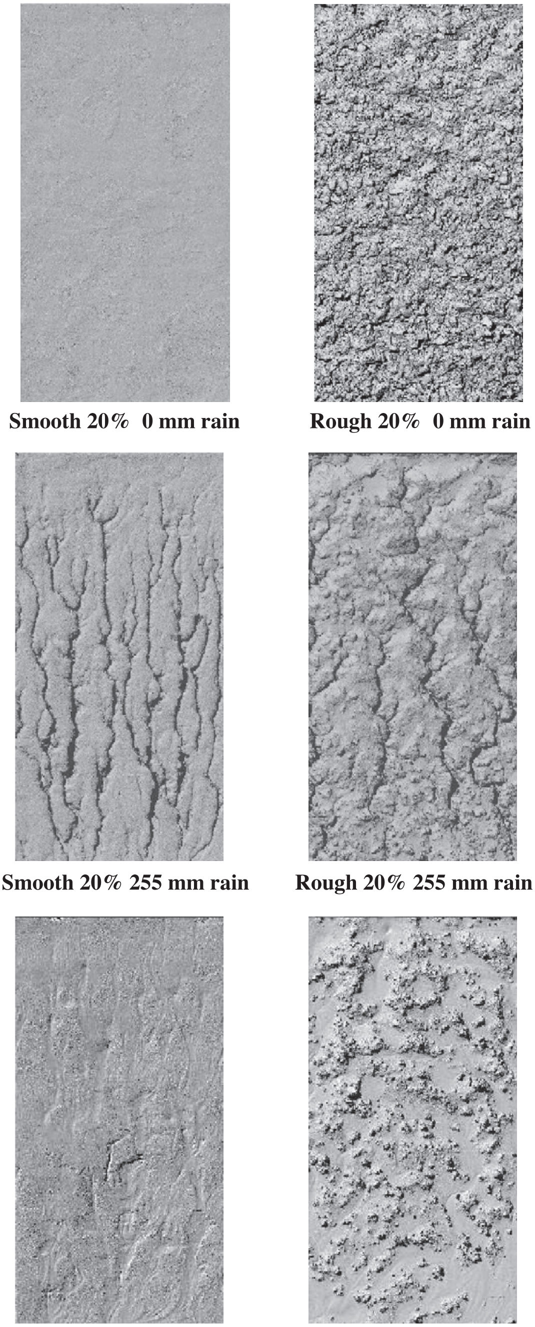

Fig. 1. Examples of the initial and final surfaces after 255 mm of rain. Plots were 2 m wide by 4 m long.

soil dry for 7 days. Then, we added additional dry soil to the flume until reaching the original soil level to compensate for sediment losses. The top 0.15 m of the soil was turned over and thoroughly mixed. The surface was carefully leveled until obtaining a smooth surface. At this point, we applied a 2-h simulated rainfall at 15 mm/h in successive steps (stopping and waiting several hours when surface runoff became significant) until completing 2 h of rainfall on the bare surface. The soil surface was then allowed to dry for 8 days using fans, and finally, a manual tillage was performed 2 days before starting the experiment. When the first replication of the treatments was completed, the top 0.16 m of the soil was replaced by new soil, and the simulations corresponding to the second replication were started.

Table 1 gives a description of the surface bulk densities (0.05 m top soil layer) measured using the excavation method (Blake and Hartge, 1986) of the initial and final surfaces. It also shows the roughness of the initial surfaces using two different indexes: the standard deviation of the individual elevation readings after removing the effects of slope and oriented roughness or random roughness (Currence and Lovely, 1970) and the tortuosity (Boiffin, 1984), which is the ratio between actual and projected (on the horizontal plane) length of a profile of the soil surface calculated after slope and oriented roughness effects were removed. In our case, the profiles for calculating tortuosity were made in the direction perpendicular to the main slope. The spacing between two consecutive profiles was 0.0015 m, totaling 2368 profiles per analyzed flume surface. The elevation readings for the roughness determination came from a digital elevation model, DEM, at 1.5-mm grid spacing of each of the three original surfaces. These DEMs were obtained through a laser scanner (Darboux and Huang, 2003), and they have been described and analyzed elsewhere (Gómez et al., 2003).

2.2. Rainfall simulations

Each experiment consisted of five consecutive rainfall simulations for each replication of a treatment starting on a freshly prepared surface. The rainfall simulations lasted 1 h each and were timed 48 h apart. The first three rainfalls had an intensity of 45 mm h^{-1}, and the last two had 60 mm h^{-1}. The last two rainfall simulations at 60 mm h^{-1} were necessary to cause rill development at the 5% slope, for which the rainfall intensity of 45 mm h^{-1} was not great enough to effect completed rill development. With this experimental design, the networks operated under bank full discharges for each treatment.

Agronomists use 48 h as a rule of thumb to estimate the period when most of the gravitational movement of the water infiltrated after a rainfall event takes place. Although

Table 1
Characteristics of the initial surfaces and final bulk density

	Initial bulk density	Final bulk density	Random roughness	Tortuosity
	kg m^{-3}	kg m^{-3}	mm	
Smooth surface	1140	1270	2.55	1.02
Rough surface	940	1240	26.24	1.75
Subsurface layers	1220			

crude, we chose that interval to start the simulations with approximately similar soil water content, while at the same time, minimizing the duration of the experiment. The initial soil water content was measured using 10 TDR probes, 0.15 m length, inserted vertically in the areas of the flume surface near its perimeter. We depended on control of the rainfall and drying time during the surface preparation to minimize the differences in soil moisture content at the beginning of the first rainfall simulation. The average volumetric water content at the beginning of the 12 experiments was 20.7% (standard deviation 1.1%) without significant differences between different treatments, although differences in initial moisture between replications varied as much as 6% (Table 2). For that reason, all the comparison between treatments means were made using a paired comparison *t*-test (Montgomery, 1991) using the initial surface moisture content, in Table 2, as the criteria to arrange the pairs.

Rainfall intensity was monitored during each rainfall simulation using eight rain gages located on the flume edges. The monitoring of intensity showed that the rainfall intensities remain stable throughout the duration of the experiment, with a coefficient of variation of 2.4%.

During each rainfall simulation, runoff samples were taken at the flume outlet at 2-min intervals from the moment that runoff started. These samples were used to calculate runoff and sediment fluxes.

2.3. Rill survey

After each of the fifth rainfall simulations, we made a survey of the flume surface, counting the number of rills and measuring their depth and width at four transects. We defined a rill in our survey of the flume surface as an area where both flow convergence was observed during the rainfall simulation, and incision of the soil surface could be visually identified after the rainfall simulation. To aid in recognizing these flow concentration areas, pictures were taken of the flume surface at different times during the rainfall simulations after dye tracer application. These four transects were located at 1.26, 2.2, 2.8 and 3.5 m from the upper end of the flume.

2.4. Area drained by each rill

Using the DEM acquired with the laser scanner after the fifth rainfall simulation, the drainage network was delineated using the steepest descent algorithm, D8 (O'Callaghan and Mark, 1984), using a critical threshold area calibrated from the rill survey to obtain the best possible match between the observed rill network and the delineated drainage

Table 2
Volumetric soil moisture content, θ_v, in the top 10 cm of soil at the start of the rainfall simulations

Treatment	Replication	θ_v (%)	
		20% Slope	5% Slope
Smooth	1	18.0	24.6
	2	23.9	19.2
Rough	1	16.6	23.9
	2	21.3	18.3

network. Using this procedure, as explained in Gómez et al. (2003), it was possible to calculate the area drained by each rill reaching the lower end of the flume.

3. Results and discussion

Fig. 1 shows an example of the initial and final surface of each roughness treatment at 20% slope and also an example of the final surface of each treatment at 5% slope. The initial surfaces at 5% were similar to those for the 20% slope. These were obtained from the DEMs acquired with the laser scanner.

3.1. Runoff

Fig. 2 presents the runoff rate for each rainfall simulation and treatment (average of two replications), and Table 3 shows the cumulative rainfall and final runoff rate for each

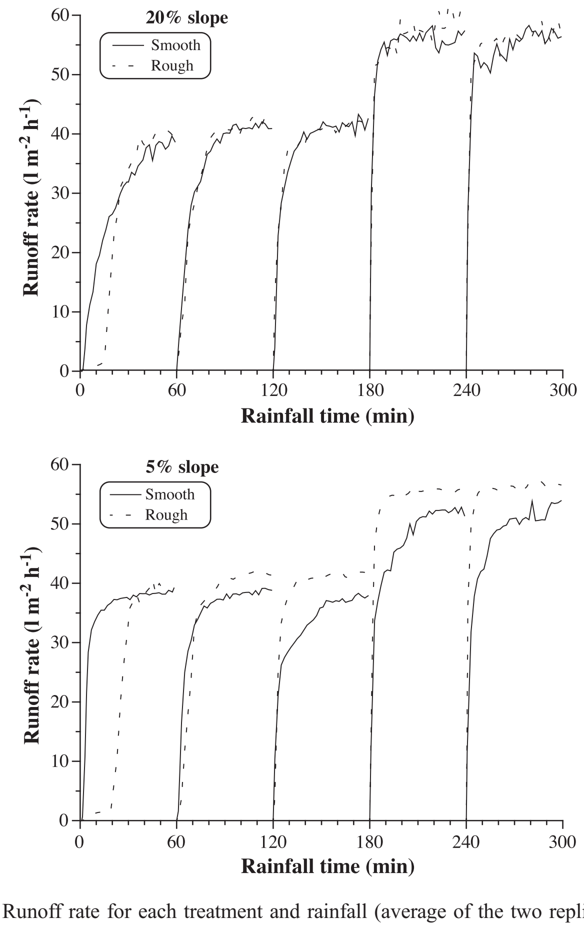

Fig. 2. Runoff rate for each treatment and rainfall (average of the two replications).

Table 3
Total runoff and final runoff rate (average last 8 min) for each rainfall event

Slope		Total runoff (l m^{-2})					Final runoff rate (l m^{-2} h^{-1})				
		Smooth		Rough			Smooth		Rough		
		1	2	1	2		1	2	1	2	
20%	1st rain, 45 mm h^{-1}	26.8	28.9	27.0	22.4	NS	36.9	40.0	40.6	39.4	NS
	2nd rain, 45 mm h^{-1}	35.7	33.4	36.8	33.0	NS	41.2	41.5	43.4	41.8	NS
	3rd rain, 45 mm h^{-1}	37.7	36.3	38.9	36.3	NS	42.0	42.6	42.6	41.4	NS
	4th rain, 60 mm h^{-1}	52.4	54.2	57.8	52.2	NS	54.8	58.6	58.5	56.0	NS
	5th rain, 60 mm h^{-1}	52.1	52.9	56.1	51.8	NS	56.6	57.1	59.4	55.7	NS
	Total	204.7	205.7	216.6	195.7	NS					
5%	1st rain, 45 mm h^{-1}	34.5	33.8	24.1	20.0	$P_{0.975}$	38.6	38.5	40.0	38.2	NS
	2nd rain, 45 mm h^{-1}	34.6	33.2	36.1	32.8	NS	39.0	39.1	43.0	40.0	NS
	3rd rain, 45 mm h^{-1}	32.8	32.1	39.0	37.0	$P_{0.975}$	38.1	37.6	43.0	40.6	$P_{0.90}$
	4th rain, 60 mm h^{-1}	45.8	46.5	52.9	52.2	$P_{0.99}$	52.1	52.3	56.1	55.1	$P_{0.95}$
	5th rain, 60 mm h^{-1}	45.0	48.2	54.8	53.0	$P_{0.90}$	53.1	54.1	56.8	56.1	$P_{0.90}$
	Total	192.7	193.8	206.9	195	NS					

Differences between treatments for that slope and rainfall event were tested using a paired comparison of means test, where pairing was done according to soil moisture similarities. P_α indicates significant differences, α being the probability level. NS indicates nonsignificance. Data for each replication, 1 and 2, are shown.

replication, rainfall and treatment. For both the 5% and the 20% slopes, there was a delay in the initial runoff from the rough surfaces; however, this delay was evident only during the first of the five rainfall applications (Fig. 2). For all treatments, the runoff rates tended to stabilize at the end of each rainfall simulation, suggesting that surface sealing reached a well-developed stage.

At 20% slope, differences in runoff rate between the two roughness treatments were small after the first few minutes of rainfall when the surface storage provided by the initial roughness was filled. The overall smoothing of the original rough surface features, the filling of depressions and the interconnecting of the rills obliterated most of the differences in runoff caused by different initial ponding conditions between the initial roughnesses (Fig. 2). As a result, neither final runoff rates nor total runoff amounts were significantly different between the two initial surface treatments at 20% slope (Table 3). Our experiments at 20% slope essentially confirmed the results of Helming et al. (1998) under a similar experimental layout at 17% slope.

At 5% slope, the effect of the surface storage on the rough surface lasted longer during the first rainfall application than at 20% slope (Fig. 2). This resulted in a significantly greater runoff amount from the smooth surface relative to the rough one during the first rainfall simulation (Table 3). The second rainfall application resulted in no significant differences in runoff; however, and after the second rainfall simulation, the rough treatment showed greater runoff amounts and final rates compared to smooth (Table 3). Because of the fact that the runoff was greater on the smooth surface in the first rainfall application and lesser in the last three, the overall total runoff amounts for the five applications were not significantly different between the two roughness treatments at 5% slope.

The reduction in runoff as a function of rougher surfaces is usually attributed to the detention storage provided by the rougher surface, as well as to the reduced tendency to sealing due to the bigger and more stable clods and their larger specific surface area that reduces the rainfall energy rate per unit area. This is consistent with our results in the early stages of the experiment, with the caveat that the influence of the detention storage on runoff disappeared quickly once all the depressions were filled and interconnected, and the trend reversed toward more runoff from the rough surface after that point in time.

The fact that there was no measured difference in the total runoff volume from the five rainfalls from the 5% slope was in general agreement with the results presented by Helming et al. (1998). However, the details of the temporal dependency of runoff between the two treatments for the current experiment were not observed in the experiment of Helming et al. (1998).

The difference in runoff behavior in our experiment between the 5% and 20% slope may be attributable to surface sealing. For the simulations at 5% slope, due to the lower erosion rate, the microrelief induced by the surface preparation remained significantly different between the roughness treatments. Therefore, a large fraction of the surface of the rougher surface was covered by a depositional crust due to sedimentation within the depressions

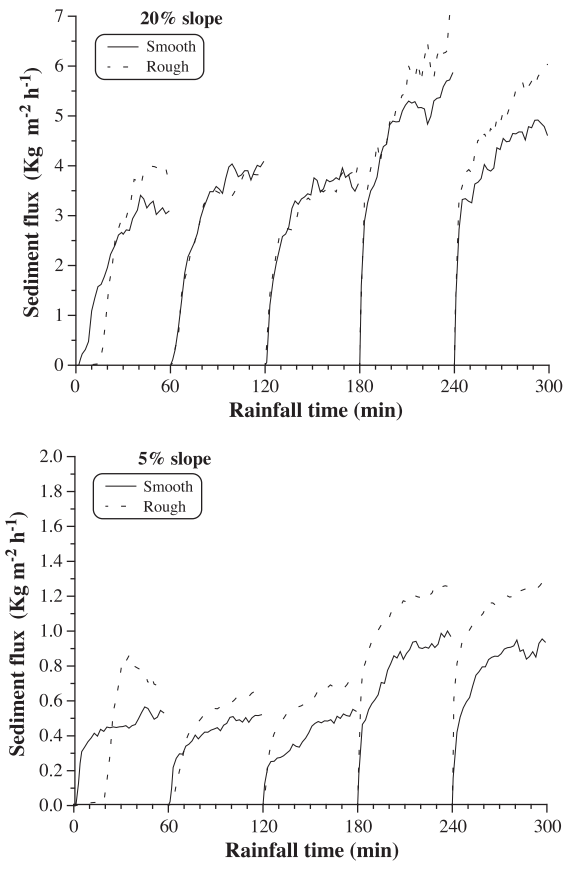

Fig. 3. Sediment flux for each treatment and rainfall (average of the two replications).

created by tillage. This feature was not observed on the smoother surface at 5% slope. Sedimentary crusts tend to be thicker and have lower infiltration rate than structural crusts (Fox et al., 1998), and this may be the reason why the rough treatment generated more runoff than smooth in our experiment during the last three rainfalls at 5% slope. The implications for prediction of tillage effect on runoff generation is that not only is the degree of surface roughness created important but also important is the influence of tillage on the distribution of depositional and structural seals through the modification of the initial microrelief.

3.2. Sediment yield

Fig. 3 illustrates the sediment yield rates for each rainfall simulation and treatment (average of two replications). Table 4 shows the cumulative sediment yield and final sediment yield rate for each replication, rainfall application and roughness treatment. In both roughness treatments, sediment rates tended to stabilize at the end of each rainfall simulation at 45 mm h^{-1} but not at 60 mm h^{-1}, probably due to the observed active rill incision and widening at the higher intensity. In general, sediment yield results exhibited a greater variability among replications compared to the runoff values. There was an initial delay in the sediment yield during the first rainfall application for the rough treatment at both slopes that paralleled the delay in runoff because of initial surface ponding.

At 20% slope, differences in sediment yield amounts between the two roughness treatments were significantly different only for the last rainfall application. Even in the case of the first rainfall application where sediment response was significantly delayed on the rough surface, the total sediment yields between roughness treatments were not significantly different because the sediment yield jumped to a much greater rate on the

Table 4
Total sediment yield and final sediment rate (average last 8 min) for each rainfall event

Slope		Total sediment (kg m^{-2})					Final sediment rate (kg m^{-2} h^{-1})				
		Smooth		Rough			Smooth		Rough		
		1	2	1	2		1	2	1	2	
20%	1st rain, 45 mm h^{-1}	2.1	2.3	2.4	2.0	NS	2.9	3.3	3.7	4.2	$P_{0.99}$
	2nd rain, 45 mm h^{-1}	3.1	2.9	2.9	2.9	NS	3.7	4.3	3.7	4.0	NS
	3rd rain, 45 mm h^{-1}	2.9	3.3	3.0	3.1	NS	3.1	4.2	3.7	4.0	NS
	4th rain, 60 mm h^{-1}	4.5	4.7	5.9	4.4	NS	5.4	6.1	8.1	5.4	NS
	5th rain, 60 mm h^{-1}	4.2	3.8	5.0	4.5	$P_{0.99}$	4.6	5.0	5.9	5.9	$P_{0.975}$
	Total	16.8	17	19.2	16.9	NS					
5%	1st rain, 45 mm h^{-1}	0.4	0.5	0.5	0.4	NS	0.5	0.6	0.7	0.7	$P_{0.99}$
	2nd rain, 45 mm h^{-1}	0.4	0.4	0.5	0.5	$P_{0.90}$	0.4	0.6	0.6	0.7	$P_{0.95}$
	3rd rain, 45 mm h^{-1}	0.3	0.5	0.5	0.6	$P_{0.975}$	0.4	0.6	0.6	0.8	$P_{0.95}$
	4th rain, 60 mm h^{-1}	0.6	0.9	0.9	1.3	$P_{0.975}$	0.8	1.2	1.1	1.4	$P_{0.99}$
	5th rain, 60 mm h^{-1}	0.6	0.9	1.0	1.2	$P_{0.95}$	0.8	1.1	1.2	1.4	$P_{0.95}$
	Total	2.3	3.2	3.4	4	$P_{0.95}$					

Differences between treatments for that slope and rainfall event were tested using a paired comparison of means test, where pairing was done according to soil moisture similarities. P_α indicates significant differences, α being the probability level. NS indicates nonsignificance. Data for each replication, 1 and 2, are shown.

rough surface once sediment began to move (Fig. 3 and Table 4). Total erosion at 20% slope was not significantly different between the two roughness treatments.

This contradicts the findings of Helming et al. (1998) who observed higher soil losses for the rougher surface at 17% slope. Helming et al. (1998) explained that their results may have been due to the increased flow concentration due to the larger clods in the rougher surface. In our experiments at 20% slope, a well-developed rill network appeared after the first rainfall event in both roughness treatments, with rill erosion apparently being the dominant process in both cases. The increased flow concentration (i.e., deeper rills) on the rougher surface compared to the smoother one did not translate into an increase in soil erosion because of the reduced number of rills (Table 5).

An analysis of the rill erosion at these surfaces with the erosion model of Laflen et al. (1997) based on sediment transport capacity, using the average rill properties, runoff, sediment and flow velocity measured during the fifth rainfall simulation, also predicted insignificant differences in erosion between both initial roughnesses for the 20% slope. This suggests that for the conditions of our experiment, with a steep slope on a bare surface of an erodible soil, the erosion rate might be controlled by the overall potential energy available as determined by the surface elevation above the flume outlet (Ijjáz-Vásquez et al., 1993) with an insignificant influence by the degree of flow concentration.

At 5% slope, clear differences in sediment rate were observed, with greater steady-state yield rates from the rough surface for each rainfall application (Fig. 3). As was the case for the 20% slope, sediment flux during the first rainfall simulation surged with the routing of the surface water stored on the surface depressions once the barriers between the depression areas started to breach and overflow. The differences in sediment rate translated into significant differences in total sediment yield between roughness treatments after the first rainfall application (Table 4).

Our results for the 5% slope treatment wherein the rougher surface produced significantly more sediment than did the smooth surface contrasts with previous observations and common assumptions (Zobeck and Onstad, 1987; Renard et al., 1997), indicating that rough surfaces produce less sediment.

A part of the reason for the greater erosion on the rough surface at 5% slope (Table 4) was probably related to the significantly greater runoff from the rough surface (Table 3).

Table 5
Rill properties after the fifth rainfall simulation

Slope		Smooth		Rough		
		1	2	1	2	
20%	Rill width [mm]	33	45	33	44	NS
	Rill depth [mm]	37	37	47	49	$P_{0.99}$
	No. rill per transect	10.5	11.5	8.5	6.5	$P_{0.90}$
5%	Rill width [mm]	72	43	70	92	NS
	Rill depth [mm]	6	4	6	6	NS
	No. rill per transect	5.0	6.2	4.4	3.8	$P_{0.90}$

Differences between treatments for that slope were tested using a paired comparison of means test, where pairing was done according to soil moisture similarities. P_α indicates significant differences, α being the probability level. NS indicates nonsignificance. Data for each replication, 1 and 2, are shown.

Other reasons may be that, at 5% slope, the initial surface features remained significantly differentiated between treatments over time, and the influence of rill erosion on the overall water erosion was diminished at 5% slope compared to 20% slope. The relatively small degree of rilling and the uniform smooth surface made for a more uniform depth of water flow across the flume, while in the rough treatment water flowed in a more concentrated manner. The implication for sediment yield under different tillage systems is that, in addition to the interaction with different resulting runoff rates, under situations of low rilling intensity, the details of the microrelief, runoff generation and different forms (i.e., rill vs. interrill) of erosion interact in an spatially and temporally dynamic fashion.

3.3. Rill properties

Table 5 shows the average properties of the rills developed after the fifth rainfall simulations. The treatments at 20% slope developed an intensively rilled surface, while the treatments at the 5% slope showed a lesser degree of rilling. At 5% slope, there were fewer rills per transect, and those rills were wider and shallower than those at

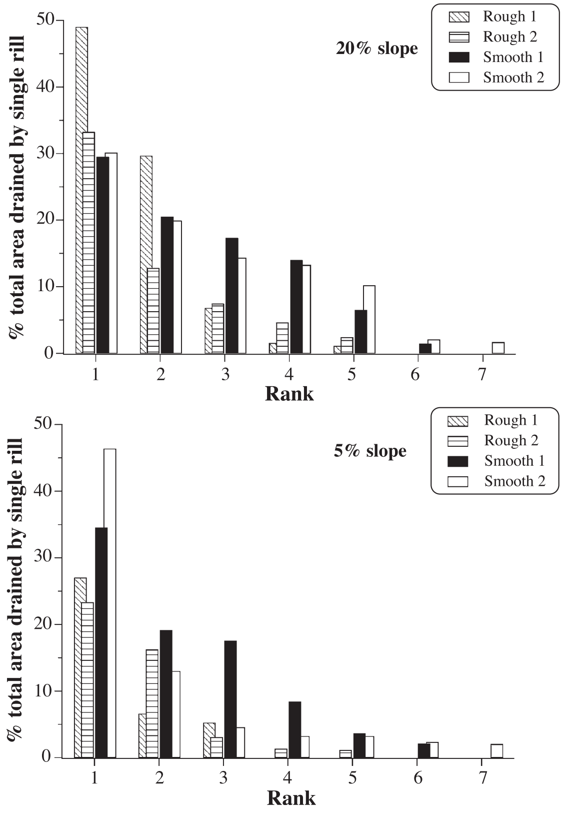

Fig. 4. Area drained by a single rill per treatment and slope determined from the DEM after the fifth rainfall simulation.

20% slope (Table 5). With both the 5% and 20% slopes, there were fewer rills on the rougher surface compared to the smooth.

Fig. 4 illustrates the area of the flume that was drained by individual rills that reached the bottom of the flume. For the rough treatment, an individual rill at 20% slope drained a larger area than did a rill for the 5% treatment. This would indicate that for the rough treatment at 5% slope, the overland flow generated from some areas was drained without producing rills. The reason for this is that the overland flow passed from one depression to another where sediment was deposited, flowing through breaching points between initially ponded areas. This was observed during the rainfall simulations, and it can be visualized in Fig. 2. On the rough surfaces, the two or three largest rills dominated the runoff leaving the flume, while for the smooth surfaces, drainage was more evenly distributed among more rills.

4. Conclusions

The results of this experiment showed that the effect of the initial soil surface roughness on runoff and sediment yield depended upon the slope steepness, with a significant effect for a moderate, 5%, slope and little or no effect for a steep, 20%, slope.

The effect of initial roughness on runoff was mixed. In all treatments, runoff was delayed at the start of the initial rainfall, but the initial reduction of runoff due to ponding was temporary. At 20% slope, no overall effect in runoff volume was measured, while at 5% slope, the trend in runoff reversed. During later rains, more runoff was observed from the initially rougher slope. This was attributed possibly to formation of a stronger depositional seal on the rough 5% treatment that inhibited infiltration. This implies that the influence of tillage induced roughness on the development and distribution of depositional seals can have a significant influence on runoff and erosion. Overall, there were no statistical differences in the sum of runoff for the five rainfall applications between the two roughness treatments.

The effect of the initial roughness on erosion depended largely on the difference between a rilling dominated scenario at 20% and one not as heavily dominated by rill erosion at 5%. At the steeper slope, differences in initial surface features translated to a different rill density but not to differences in runoff or sediment yield. The increased erosion in the fewer number of deeper fewer rills on the initially rougher surface was equaled by the erosion produced in the more numerous rills that appeared on the smoother surface. At the 5% slope, erosion was greater on the initially rougher slope because of the greater runoff amounts and because on the smooth surface flow was shallow and broad while flow was somewhat concentrated on the rough surface because of the flow around the roughness elements themselves.

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