Soil surface roughness under tillage practices and its consequences for water and sediment losses

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Abstract

The present study aims to determine the effects of soil management practices on soil surface roughness and the consequences of these phenomena on water and sediment losses. Laboratory experiment was conducted on a Chernozems clayey soil subjected to a sequence of two 30 min simulated rainfall of 50.8 mm h⁻¹ and 114.3 mm h⁻¹ and four soil management practices: contour tillage (CT), downhill tillage (DT), no-tillage simulated (NTs) and bare soil (BS). Soil surface roughness was evaluated using a laser distance meter. Results showed that the soil tillage in downhill or contour increased soil roughness by 2.90 and 2.76, respectively, reducing the water losses under low rain intensity by 12.8% and 6.4%. Soil surface roughness quickly changed after the onset of rain, and higher values of changes in soil roughness were observed for contour (22.73%) and downhill tillage (21.05%) managements. Soil coverage factor and the direction of tillage were the most important characteristics in contrast with soil surface roughness to reduce the sediment losses. No-tillage simulated (0.59 t ha⁻¹) and contour tillage (1.30 t ha⁻¹) were the soil management practices with lower sediment losses compared to other managements studied. The principal theoretical implication of this study is that land use planning with agriculture, livestock must be designed to prevent the soil from being exposed, or if exposed, tillage in contour should be adopted. The input of litter on soil surface had an important role in reducing the sediment and water losses.

Keywords: Runoff, sediment losses, water losses

1. Introduction

Soil surface roughness is related to the microrelief and refers to wrinkling of the surface, caused by micro elevations and microdepressions spatially distributed that is directly related to soil management

practices (Bertol *et al.*, 2008; Bramorski *et al.*, 2012; Dalla Rosa *et al.*, 2012; Vásquez *et al.*, 2005). Although ephemeral, the soil surface roughness is induced by various methods of soil preparation and is

important in conservation tillage systems (Bramorski *et al.*, 2012; Vázquez *et al.*, 2010).

Soil surface roughness has been often ignored in high-slope regions, where water erosion is a prevalent problem (Mendonça *et al.*, 2015). The increase in soil roughness increases the water infiltration into the soil and the water retention on the surface and reduces the speed and volume of runoff, leading to diminish or mitigate damages caused by water erosion (Álvarez-Mozos *et al.*, 2011; Kamphorst *et al.*, 2000).

Previous studies have reported that the higher number of soil depressions lead to increase in water infiltration in the soil profile allowing it to reduce runoff (Bertol *et al.*, 2008; Bramorski *et al.*, 2012). Prior reports also suggest that the presence of crop residues on soil may reduce the impact of raindrops, elevating the soil resistance to erosion process (Bertol *et al.*, 2007; Brunel *et al.*, 2013; Chaplot *et al.*, 2012). These observations indicate soil cover and surface roughness as important factors that influence the erosion. These factors are responsible for almost all of water storage and sediment retention on soil surface (Bertol *et al.*, 2008; Kamphorst *et al.*, 2000) and they should be considered in soil management practices. Reducing runoff in agricultural and livestock areas implies an improvement of soil quality, since decreasing water loss, sediment and nutrients that are essential to develop crops (Thierfelder and Wall 2012; Teague *et al.*, 2010; Teague *et al.*, 2011). Many studies have demonstrated that soil preparation leads to increased roughness in soil under no-tillage, however, the magnitude is influenced by soil type and soil mineralogy (Bertol *et al.*, 2006; Bertol *et al.*, 2008; Bramoski *et al.*, 2012). However, little is known regarding the direction of soil preparation influencing the roughness and the loss of water

and sediments (Barbosa *et al.*, 2010; Luciano *et al.*, 2009). In addition, studies relating soil cover to the roughness are very few.

Conventional tillage or no-tillage are the most common soil management practices in different agricultural regions of the world (Agostini *et al.*, 2012; Brunel *et al.*, 2013; Brunel-Saldias *et al.*, 2016). Nevertheless, part of agriculture and livestock regions are located in high slope reliefs, where studies concerning soil management practices are scarce in comparison with flat lands. To high slope areas, information about how the soil roughness and soil cover can influence soil quality can be important in view to guide recommendations of soil management practices. The first step is conducting experiment in small scale, that permit isolating variables which can lead some interference especially variables related with climate and soil as observed in field experiments. In this sense, the objective of this study is to evaluate the effects of soil roughness on soil and water losses under simulated rainfall.

2. Material and Methods

2.1. Plots preparation and soil managements

A series of experiments were conducted under rainfall simulation at the Agricultural and Biological Engineering Department of the University of Illinois. Two tilting soil chambers (3.60 m of ramp length and 1.50 m width, with 17 % of slope) filled with Chernozems clayey (IUSS Working Group WRB, 2006) (Table 1 and Figure 1) were used to investigate soil erosion patterns under different management practices. More details about the soil chambers, please refer to Bhattarai *et al.* (2011).

Figure 1. Rainfall simulator, soil chambers and soil managements. CT - Contour tillage; DT - Downhill tillage; NTs – No tillage simulated; BS- Bare soil.

Table 1. Physical attributes of the Chernozems clayey used on the runoff evaluation

Sand	Silt	Clay	Bd	Ko
-----g kg ⁻¹ -----			kg dm ⁻³	cm h ⁻¹
110	140	750	1.50	3.30

Bd - Bulk Density; Ko - Hydraulic conductivity.

Four soil managements practices were studied: (a) Contour tillage (CT): implemented manually, tilling the soil opposite the slope in a depth of 0.15 m; (b) Downhill tillage (DT): implemented manually, tilling the soil following the direction of the slope in a depth of 0.15 m; (c) No-tillage simulated (NTs): no-tillage simulated implemented using equivalent of 24 t ha⁻¹ of wheat straw as soil cover; and (d) Bare soil (BS): without tillage or straw.

2.2. Rainfall simulation

For the experiments two rainfall intensities were used corresponding to 50.3 mm h⁻¹ (2 in h⁻¹) and 114.13 mm h⁻¹ (4.5 in h⁻¹) for 30 min, which represents 1 and 50-year events respectively in Central Illinois. The rainfall simulator consisted of two modules, 1.3 m apart, each containing five Spraying Systems (Wheaton, IL) Veejet

80100 nozzles that operate at 41 kPa (Figure 1) (Bhat-tarai *et al.*, 2011). The rainfall simulator modules are located 10 m from the floor, because majority of the drops attain terminal velocity by the time they hit the floor, thus simulating near-natural rainfall events (Hirschi *et al.*, 1990). We ensured to maintain similar soil moisture (30 ± 5 %) in each soil management before simulating rain to avoid the interference of the water content in runoff evaluation. The experiments were carried out with a slope of 17 %, which was the maximum adjustable slope of the soil chamber.

2.3. Soil surface scanner

The data collection of soil surface was carried out using a laser distance meter (Leica 3D Disto®) programmed to make automatic readings spaced at 5 cm with ~810 readings per plot before each event. The

roughness of the soil was evaluated at “zero stage”, immediately after preparation of the soil, and after each rain simulation.

2.4. Soil and water collection

The runoff from each management was collected in large bottles with 23 L capacity. In order to determine the amount of sediment, five sub samples (25 ml each) were collected after thoroughly mixing the runoff water. The aliquot samples were placed in the oven for 48 h until all the water was evaporated. The total amount of sediments and water losses were converted to kilogram of sediments per hectare, and mm of water.

2.5. Data analysis

The analysis of soil surface after collection of data was processed using Surfer® software. To calculate the soil roughness, a method proposed by Allmaras *et al.* (1966) and modified by Currence and Lovely (1970) was used, by multiplying the standard deviation of the

elevation logarithms by the mean elevations. The soil roughness values were computed before the rain (after the tillage), and after each simulated rainfall. The results of water and sediment losses were presented as total accumulated in each simulated rain event, and the sum of two simulated rains.

3. Results

Figure 2 shows the soil surface before the rainfall simulation. The soil tillage raised the soil surface above the original level, with a direct effect on the soil surface roughness for downhill and contour tillage managements. The large amount of litter deposited on soil surface in no-tillage simulated management also increase soil roughness (Table 2 and Figure 2).

As shown in Figure 2, superficially bare soil management exhibited similar characteristics to the no-tillage simulated management, whereas downhill and contour tillage managements have distinct surface characteristics.

Table 2. Index of soil surface roughness in different soil managements prior and after two rainfall simulations

Treatments	Surface roughness (mm)				
	Before Rain	After rain			
		50.8 mm h ⁻¹	DSR (%) ²	114.3 mm h ⁻¹	DSR (%)
Contour Tillage	7.03 (2.76) ¹	5.55	21.05	5.33	3.96
Downhill Tillage	7.17 (2.90)	5.54	22.73	5.52	0.36
No-Tillage simulated	4.34 (0.08)	4.28	1.38	4.28	0.00
Bare soil	4.26	4.23	0.70	4.20	0.71

¹Values of increase of soil surface roughness in comparison to the Bare soil. ²DSR: Decrease of soil roughness.

Figure 2. Diagram block of soil surface roughness before the rainfall simulations.

Before the rain events, higher soil surface roughness was related to the downhill and contour tillage management, followed by no-tillage simulated management and bare soil (Table 2). After the rain simulations, a decrease in soil surface roughness occurred, especially after the first rain (50.8 mm h^{-1}), with more effects on higher values of this parameter.

A greater decrease in the soil roughness was observed after the first simulated rain (50.8 mm h^{-1}) for CT and DT managements. The index of roughness decrease in these managements were 22.73% in the first and 21.05% for the second, while the decrease of soil roughness in the NTs and BS management were 1.38% and 0.71% respectively (Table 2).

For the second rain intensity (114.3 mm h^{-1}), the decrease in soil roughness overall was lower compared

to the first rainfall event. The NTs management did not change the soil surface after the second rain (114.3 mm h^{-1}), while the CT, DT and BS managements decreased the surface roughness by 3.96%, 0.36% and 0.71% respectively (Table 2).

It can be seen from the data in Table 3 that the water loss for 50.8 mm h^{-1} intensity event was lower for the CT (3.26 mm or 6.41%) and DT (6.52 mm or 12.83%) managements, and was higher for the NTs (9.78 mm or 19.25%) and BS (13.04 mm or 25.66%) managements. For the second simulated rain (114.3 mm h^{-1}), the BS and CT management resulted in the high values of losses with 58.33 mm (or 51.03%) and 53.99 mm (or 47.23%), respectively. It indicates the influence of soil roughness on the water losses for these managements.

Table 3. Water and sediment losses in different soil managements in two rainfall simulations

Treatments	Water (mm)	Sediment (t ha ⁻¹)
50.8 mm h ⁻¹		
Contour Tillage	3.26 (6.41) ¹	0.07
Downhill Tillage	6.52 (12.83)	0.04
No-Tillage simulated	9.78 (19.25)	0.02
Bare soil	13.04 (25.66)	1.73
114.3 mm h ⁻¹		
Contour Tillage	53.99 (47.23)	1.22
Downhill Tillage	47.10 (41.20)	8.41
No-Tillage simulated	45.65 (39.93)	0.56
Bare soil	58.33 (51.03)	8.03

¹In parentheses is shown the percentage (%) of water loss in total rain.

Evaluating the sediment loss in the rain intensity of 50.8 mm h⁻¹, the soil coverage and the tillage were important factors to reduce the losses. Numerically lower values of sediment losses were found in NTs (0.02 t ha⁻¹), DT (0.04 t ha⁻¹) and CT (0.07 t ha⁻¹) managements, while the highest values were found in the BS management with 1.73 t ha⁻¹. For the simulated rain with intensity of 114.3 mm h⁻¹, the NTs and CT managements showed lower values of sediment loss with 0.56 t ha⁻¹ and 1.22 t ha⁻¹, respectively (Table 3). It was also observed that the mean value of soil roughness has a relation with the total amount of water lost

(Table 4). For different managements, even in with a litter, increase on the soil roughness, as noted in NTs management, promoted a decrease in water losses when compared to BS management. It was observed that the average water loss decreased by 22.82% for these managements compared to BS management.

For sediment losses, similar pattern was observed. The management had an influence on the sediment losses. Compared to BS management, the NTs and CT management reduced the sediment losses by 93.96 % and 86.69 %, while the DT management reduced the sediment losses by 9.41 % (Table 4).

Table 4. Mean of soil surface roughness and total amount of water and sediment losses in different soil managements in two rainfall simulations

Treatments	Surface roughness	Water	Sediment
	mm	mm	t ha ⁻¹
Contour Tillage	5.97	57.25	1.30
Downhill Tillage	6.08	53.62	8.85
No-Tillage simulated	4.31	55.43	0.59
Bare soil	4.23	71.38	9.77

4. Discussion

An increase in soil roughness after the soil tillage in the present study confirm the findings from several earlier studies (Bertol *et al.*, 2006; Bertol *et al.*, 2008; Bertol *et al.*, 2010; Bramorski *et al.*, 2012). The soil roughness values obtained for the CT, DT, NTs and BS managements for this study were close to those found in others studies with different soil and climate conditions (Bertol *et al.*, 2006; Bramorski *et al.*, 2012).

In general, the flow of water on a soil surface with high roughness results in low water losses compared to a surface with low roughness, resulting in lower total loss of sediment (Cogo *et al.*, 1984). However, our data showed that the soil cover and the direction of cultivation were more influential than the increase in roughness when evaluating sediment losses.

It was observed that the NTs management, even with high deposition of litter, promoted a low increase in soil surface roughness. However, this high deposition lead to low values of sediment losses which agrees with the findings of Locke *et al.* (2015) and Rhoton *et al.* (2002). In the present study, the soil cover reduced the impact of rain drops falling directly on the soil, increasing the soil erosion resistance (Potter *et al.*, 1995). In addition, the litter deposited in the soil could be used as a filter holding the sediment in NTs management.

CT and DT managements involved ridges of various sizes raising the soil roughness and this worked as a physical barrier to runoff, reducing the water losses. However, this was true for the rain with low intensity (50.8 mm h⁻¹) only.

Cultivation following the slope direction functions as drainage canals, where water runoff is concentrated along the slope, dissolving the ridges and carrying the soil with greater energy (Luciano *et al.*, 2009). It can be an explanation for high values of sediment losses found in DT management.

In the CT management, the reduction in the sediment loss can be attributed to the increase in soil surface roughness in contour. This creates ridges that are arranged transversely on a hill, reducing the speed of runoff and filtering the sediment contained therein (Cogo *et al.*, 2007; Luciano *et al.*, 2009). Although the CT management in the present study has demonstrated lower boundary of sediment loss, when compared to the DT and BS managements (Table 3), the high values of water loss found for this management may be due to the partial breaking of lumps after rainfall agreeing with the results reported by Luciano *et al.* (2009).

This study has been able to demonstrate that the rainfall could reduce soil surface roughness, with a tendency of decreasing more markedly in CT and DT managements, confirming observations described in literature (Cogo *et al.*, 1984; Bertol *et al.*, 2006; Bertol *et al.*, 2008). This behavior was noted, particularly after the first rain simulation, where the decay rate was higher, reaching 22.73% (Table 2).

The decrease in soil roughness is related to the kinetic energy of drops impacting directly on the soil which broke the soil aggregates and micro elevations. This is associated with the surface runoff eroding the soil, increasing sediments transport and re-depositions (Bertol *et al.*, 2006). As the micro depressions were eroded after the first rain, the effect on the soil roughness was minimum for the second rain which had higher intensity and volume of water.

Although the decay rate has been considerable, the values were well below than those reported by Bertol *et al.* (2008) with similar management. This difference can be attributed to the soil conditions were different from the present study.

The relative reduction in roughness, while comparing the CT and DT managements with NTs and BS managements, is explained by the fact that the first two treatments had higher initial roughness values.

However, the small superficial changes in rates of roughness after the rain simulations for the BS management, associated with high values of losses in water and sediment, may indicate that the runoff in this management occurred rather evenly, similar to what was observed in the field sheet erosion. In addition, two rain simulations were not sufficient to develop rills in this area, which could lead to increase in the surface roughness. It was observed that decrease in roughness was possibly due to lost soils that were deposited in the areas of microdepressions.

The small change in soil roughness noted in the NTs management may be related to low soil loss values, which only promoted the accommodation of the litter in the soil surface after the first rain simulated (Table 2).

5. Conclusions

This study demonstrated that the soil cultivation in downhill or contour can lead to increase in soil roughness. However this experiment confirmed that this characteristic quickly changed after the onset of rains. Soil coverage factor and the direction of tillage were the most important characteristics for sediment losses compared to soil surface roughness. NTs and CT managements showed lower values of sediment losses.

The principal theoretical implication of this study is that land use planning with agriculture or livestock must be designed to prevent the soil from being exposed or if exposed, tillage in contour should be adopted. Other important theoretical implication was that the input of litter on soil surface has an important role in reducing the sediment and water losses.

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