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Changes in soil surface properties under simulated rainfall and the effect of surface roughness on runoff, infiltration and soil loss

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ABSTRACT

Soil erosion by water is a result of detachment of particles or small aggregates from the soil surface followed by transport of the detached material. One of the elements that affects surface runoff and soil erosion is the soil surface roughness (SSR). Prior research reports that increasing SSR reduces generation of runoff and soil loss. In addition to that, it is widely reported that across-slope oriented roughness is better at controlling soil and water losses. However, to date there have been few studies into the effect of both magnitude and orientation of SSR on runoff, infiltration and soil erosion at the sub process level (i.e. by raindrop splash and overland flow), occurring simultaneously. In this study, the effects of up-down-slope oriented SSR (Treatment A), across-slope oriented SSR (Treatment B) and random SSR (Treatment C) were compared, along with a smooth surface (Treatment D). A moderate slope gradient of 10 %, a simulated rainfall intensity of 90 mm hr^{-1} and storm durations of 15 or 30 min were considered. The SSR was measured using the chain method, before and after the rainfall event. Images of the soil surface were taken using a hand-held laser scanner to monitor the effect of rainfall on the surface morphology. The outcome of this study shows that rainfall erosivity increases the SSR of the initially smooth surface, but decreases that of the initially rough surface, particularly in the random SSR treatment, where the decrease in SSR was 64 % of the pre-rainfall condition. This was due to the effects of raindrop impacts and overland flow. The random SSR treatment generated significantly more runoff and soil loss, and less infiltration than all other treatments ($p < 0.001$), but for raindrop splash erosion, there was no significant difference between random SSR and the other treatments. Contrary to expectations, the across-slope oriented SSR did not always reduce runoff and soil erosion compared to the up-down-slope orientation. This can be explained by degradation of surface microtopography by rainfall and runoff, as confirmed by the post-rainfall SSR measurements.

1. Introduction

Soil erosion is one of the most serious environmental problems in the world. One of the factors that affects surface runoff generation and soil erosion is soil surface roughness (SSR) which describes irregularities in the soil surface (Morgan et al., 1998). Definitions of SSR depend on the category of surface roughness and its orders of magnitude (Bullard et al., 2018a; Vermang et al., 2013; Römkens and Wang, 1986; Thomsen et al., 2015). Four main categories of soil surface roughness are recognized: (i) microrelief variations, which are due to individual particles, determined by the soil type, (ii) random roughness, which is due to the non-directional arrangement of soil aggregates, (iii) oriented roughness, which is unidirectional and describes the systematic topographical variations caused by field operations such as tillage and ridging, and (iv) greater orders of roughness, representing elevation variations at the field or landscape scale. Random and oriented roughness (categories ii and iii) have been the focus of many studies because they are determined by land management practices. They also affect various hydrologic and soil erosion processes on arable land (Govers et al., 2000). In agricultural systems, soil management practices induce changes in the soil

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microrelief (Bramorski et al., 2012; Dalla Rosa et al., 2012; Vázquez et al., 2005), and different types of tillage affect the degree of soil surface roughness (da Rocha Junior et al., 2016). Soil surface roughness affects the time for runoff initiation during or after rainfall, the amount of soil and water losses, and the amount of soil lost through rainsplash erosion. SSR also affects the way rainfall alters the surface roughness. The multitude of these processes is however rarely considered or quantified.

Some studies have found that rough surfaces delay runoff initiation during rainfall events, by trapping water in the depressions on the soil surface, so encouraging water infiltration (Darboux et al., 2004; Darboux and Huang, 2005; Vermang et al., 2015). In this way, tillage on the contour also delays runoff initiation time (Zhao et al., 2014b), regardless of rainfall intensity and slope gradient (Zhao et al., 2021). However, any delay in the time to runoff initiation might decrease with successive rain events (Darboux et al., 2004) to a level where there is no difference in runoff generation delay between initially rough and smooth surfaces.

It is widely reported that total runoff and soil loss decrease with increasing magnitude of surface roughness (e.g. Zheng et al., 2014). According to Cogo et al. (1984), increased surface roughness induced by tillage reduces soil erosion by (i) storing water in the surface depressions which promotes infiltration and reduces runoff generation, (ii) reducing runoff flow velocity which decreases the capacity of flow to detach and then transport soil particles (Cogo et al., 1983), (iii) trapping detached sediment in the surface depressions created by roughness, and (iv) preventing soil detachment by raindrops by the buffering, protective effect of any surface ponded water (Gao et al., 2003). Zhao et al. (2014b) and Idowu et al. (2001) simulated rough and smooth surfaces under a high rainfall intensity and found that increasing roughness reduced soil losses by up to 50 %. Zhao et al. (2014a) also found that soil loss for the smooth surface was significantly higher than that for the rough surface, regardless of the rainfall intensities. However, no significant difference in runoff was found between rough and smooth surfaces as the rainfall intensity increases. This is because the surface microtopography decreased and reduced the effective surface depression storage. On the other hand, the results of Darboux and Huang (2005) did not have the same conclusions. Although the rough surfaces with initial depressions delayed the time to runoff initiation, they produced 10 % greater water flux than the initially smooth surfaces, once the runoff reached an apparent steady state. This was due to the sharp decrease in the surface depressions' storage capacity. Regarding the soil loss and sediment concentration, the authors found that the effect of roughness was non-significant, and Darboux et al. (2004) explained that there was no firm conclusion regarding the decreased soil loss from the rough surfaces. Helming et al. (1998) indicated that during an initial storm, runoff concentrated immediately between the soil clods of a rough surface, routing the water within several surface flow paths. The concentrated flow had higher capacity for soil detachment and sediment transport, which explains the greater soil loss for the rough surfaces. This effect was even greater on steeper slopes. Similarly, Römkens et al. (2001) found that initially smooth surfaces yielded less soil loss than initially rough surfaces, due to differences in the runoff regime, although the roughness treatment was applied differently (by sieving the soil to different aggregate sizes). There is therefore no consensus on whether random SSR increases, decreases or have no effect on runoff and soil loss. The reason for these mixed results probably lies in different experimental combinations, such as roughness characteristics, soil properties, and rainfall intensities and durations.

Regarding oriented roughness, it is generally thought that tillage direction can either enhance or reduce runoff erosivity, depending on whether the operation (e.g. ploughing, ridging) is applied parallel to the slope direction (up- and downslope) or perpendicular to the slope (across-slope). Up- and downslope tillage can increase soil erosion because it tends to channel any surface flow down the slope, increasing both the volume and velocity of runoff and its kinetic energy to detach, entrain and transport soil particles (Hou et al., 2021; da Rocha Junior et al., 2016). Across-slope tillage (also known as contour tillage) delays the runoff initiation time (Luciano et al., 2009) and can limit soil erosion, due to the effect of perpendicular ridges acting as barriers, behind which surface runoff pools and any entrained sediments are trapped and stored (Gebreegziabher et al., 2009; Stevens et al., 2009; da Rocha Junior et al., 2016; Zhao et al., 2021). However, Quinton and Catt (2004) found that the mean event soil loss was not significantly different between the two cultivation orientations. Although contour cultivation is assumed to be an appropriate soil conservation measure (da Rocha Junior et al., 2018), it is less effective on steep slopes (Alvarez-Mozos et al., 2011; Chambers et al., 2000; USDA, 2017). This is because it can result in major concentrations of runoff in low spots along the ridges, which may overtop and breach the ridges, thus increasing the risk of erosion (Morgan, 1992).

Raindrop splash erosion is a major component of soil erosion by rainfall because it is considered the main process responsible for initial soil detachment (Morgan, 2005). The effect of surface roughness on splash erosion is not a straightforward process (Zumr et al., 2020). Wu et al. (2016) concluded that most splash erosion investigations had been conducted on a smooth soil surface and little research had considered rough surfaces. Therefore, they considered that in their study and found that soil detachment rates on the rough surfaces were greater than those on the smooth surfaces. However, these differences between roughness treatments were not clearly explained. Other authors found the opposite trend, of decreasing splash erosion with increasing roughness. There are different types of devices that measure splash erosion but as a separate process. To improve understanding of soil erosion mechanisms, it is important to consider all soil erosion processes both separately and in combination, and yet few studies considered measuring, simultaneously, both splash erosion and soil loss by runoff.

Under the influence of rainfall, the roughness of a soil surface changes over time. This roughness evolution is influenced by the volume and intensity of rainfall. In general, SSR decreases during rainfall events because the kinetic energy of the impacting raindrops causes breakdown of soil aggregates on the exposed surface (Eltz & Norton, 1997; da Rocha Junior et al., 2016; Lampurlanés & Cantero-Martínez, 2006; Panachuki et al., 2010). However, Dalla Rosa et al. (2012) noted that there was an increase in the surface roughness at the beginning of the rainfall event due to fragmentation of larger aggregates. As the duration of rainfall increases, these aggregates were further destroyed, which then decreased the surface roughness. On the other hand, initial smooth surfaces might become rougher during rainfall, due to micro-rill development on the soil surface (Huang and Bradford, 1992; Römkens et al., 2001).

The aim of this study is to obtain a better mechanistic understanding of soil erosion processes and the hydrological response of soils occurring simultaneously. To date, there have been few studies into the effect of both magnitude and orientation of SSR on runoff, infiltration and soil erosion (i.e. by raindrop splash and overland flow), occurring simultaneously. Among them, rarely are the studies that quantified the changes in the SSR post-rainfall event to explain the erosion results. The objectives of our research are a) to study the changes in the different soil surface morphologies due to rainfall and overland flow, and b) to compare the effects of up-down-slope oriented roughness, across-slope oriented roughness and random roughness, along with a smooth surface on soil and water losses under simulated rainfall. We used a slope gradient suitable for arable operations, and rainfall events (intensity and durations) and a soil texture comparable to those found in soil erosion prone regions.

2. Materials and methods

2.1. Erosion trays preparation

An air-dried sandy loam soil (16 % clay, 27 % silt and 56 % sand) was sieved through a 4 mm mesh screen and packed into erosion trays of 50 cm length, 25 cm width and 8.5 cm depth. It moisture content was 2.6 %.

Each tray was packed with 14.9 kg of sieved soil, in thin layers, giving a bulk density of 1.4 g/cm^3, typical for natural sandy loam soil. During packing, each layer of 1.65 kg was compacted using a soil packer, using the same number and intensity of strikes per layer, to achieve a uniform bulk density throughout the profile. The trays were filled up with soil to the level of a V-shaped runoff outlet from which surface runoff samples (along with sediment in the runoff) would be collected during the rainfall event. Each erosion tray was put on a base that contained a perforated steel sheet covered with voile, which prevented the packed soil from falling through, but allowed any infiltrated water to drain and reach the infiltrate outlet. This also allowed the trays to wet up to the desired initial soil moisture content via capillary action, as described below.

The soil erosion trays were then prepared to simulate different soil surface roughness treatments (Fig. 1), representing different tillage and cultivation practices, namely: a) oriented roughness – up/downslope direction, b) oriented roughness – across slope direction, c) random roughness – non directional, and d) smooth surface – with no roughness treatment applied, hereafter referred to as Treatment A, B, C and D, respectively.

Each treatment was replicated eight times, resulting in 32 erosion trays. The soil surface in Treatment D was left intact, to simulate the smooth surface. Treatments A and B were applied to the air-dried soil using a profile meter to obtain the oriented roughness in parallel to the slope direction and perpendicular to the slope direction, respectively. The profile meter was adjusted to give a wave-like shape of ridges and furrows of 0.7 cm height and depth, respectively, and with a spacing of 6.25 cm between ridges. As a result, four ridges were obtained in Treatment A and eight ridges in Treatment B (Fig. 1). The profile meter was slowly dragged up and down the slope (Treatment A) or across the slope (Treatment B) until the roughness treatment required was evenly imparted to the soil surface. Treatment C was applied on a moist soil to obtain soil aggregates, representing random roughness. A metal rake was used at a soil depth of approximately 1 cm, at different directions until clods covered the entire soil surface, representing a random roughness (Fig. 1). The surface was measured to make sure the roughness treatment applied to the eight replicates was similar.

Soil trays were put in a tank filled with water that reached the trays' base, allowing the soils to wet up by capillary rise for a period of 72 h. The erosion trays were then removed from the water tank and drained for another 72 h. Moisture content measurements were taken using a hand-held Delta-T HH2/SM150T soil moisture probe at the centre of each erosion tray.

There were no significant differences in initial soil moisture content between the erosion trays at the start of the rainfall event. The volumetric moisture content measured with the probe gave a mean of 42.67 % with a variation of 3.76 % between the trays. This is close to an estimated porosity value of 0.47, assuming a particle density of 2.65 g/cm^3, which indicates that the soil was near saturation.

2.2. Rainfall simulator calibration

A pressurised water, nozzle rainfall simulator was calibrated to deliver representative rainfall events (intensity, duration, associated return periods and drop size distribution) that reflect current and future conditions (Table 1).

The rainfall simulator was calibrated by varying the water supply pressure, ranging between 0.5 and 0.7 bar, and by varying the height of the nozzle between 1 m and 1.9 m. A number of locations under the rainfall nozzle were tested for consistent delivery of the desired rainfall characteristics. The slope gradient of the erosion trays was set at 6 degrees (~10 %), representative of typical arable field conditions.

The rainfall intensity (RI, mm hr^{-1}) was calculated using Eq. (1), where V is volume of rain collected (mL), S is surface area of the tray (cm^2), t is duration of the test (min).

Table 1
Duration and occurrence of the selected rainfall event characteristics.

Rainfall intensity (mm hr^{-1})	Duration (mins)	Return period (years)
90	15	35
	30	150 (extrapolated)

Fig. 1. Four roughness treatments applied to a sandy loam soil in erosion trays: oriented roughness – up/downslope direction (A), oriented roughness – across slope direction (B), random roughness – non directional (C), and smooth surface – with no roughness treatment applied (D).

$$RI = \frac{V}{S} \text{ x } \frac{60}{t} \text{ x } 10 \quad (1)$$

The nozzle that produced the desired intensity was a LECHLER 460.888.30.CG, placed at 185 cm above the soil surface, and the pressure at the nozzle was maintained at 0.3 bar (supply pressure of 0.5 bar). The positions under the simulator that received the desirable rainfall intensity were identified as locations of the erosion trays during the rainfall simulation experiments. Rainfall catch cups were placed next to the erosion trays during each run to ensure consistent rainfall application.

A laser optical disdrometer (LOD), positioned at 6 different locations under the rainfall simulator, was used twice during the experiment to measure raindrops' size, volume and kinetic energy to ensure representative and repeatable rainfall properties. The measurements were repeated five times for each of the six target positions. The mean values of the 60 final outputs are summarized in Table 2. The KE_t of the simulated rainfall (90 mm hr^{-1}) measured in this study is consistent with the correlation between rainfall intensity and kinetic energy presented by Shin et al. (2016).

2.3. Measurements

2.3.1. Soil surface roughness

Images of the soil surface were taken to visualize the changes in the morphology due to rainfall. For this, a laser scanner (Creaform EXAscan 3D Handscanner) was used, along with XVelements, a powerful integrated 3D scanning software. The scans were converted and processed using Geomagic Studio® software, then the 3D surface areas were computed.

Soil surface roughness was measured using the chain method, before and after the rainfall event to assess the effect of rainfall and overland flow on the soil surface morphology. In the fine chain method proposed by Morgan et al. (1993), the soil surface roughness (SSR, cm m^{-1} or %) is defined as the ratio of the straight-line distance between two points on the ground (X) to the actual distance measured over all the microtopographic irregularities (Y) (Fig. 2). To be a fair test, the denominator of the SSR equation should be the same value in both measurements before and after the rainfall event. Therefore, the equation proposed by Morgan et al. (1993) was slightly modified (Eq. (2)):

$$SSR = \frac{Y - X}{X} \text{x} 100 \quad (2)$$

For Treatment A, three readings of roughness measurements were taken across the width of the erosion tray, because this Treatment presents an up- and downslope (i.e. unidirectional) oriented roughness. For Treatment B, three readings of roughness measurements were taken down the length of the erosion tray, because this Treatment presents an across-slope (i.e. unidirectional) oriented roughness. For Treatments C and D, six readings of roughness measurements were taken (three across the width and three down the length of the tray), because these treatments present the random roughness (non-directional) and a smooth surface, respectively. For each treatment, SSR is the mean of these measurements. The link size of the chain was of 0.5 mm which enabled us to measure the microrelief on the soil surface.

2.3.2. Runoff – Infiltration – Soil loss

For each erosion tray, total volumes of surface runoff and infiltrate were collected after 15 and 30 min from the tray's outlet and the base's outlet, respectively, via a system of pipes and buckets, and measured using measuring cylinders. The time taken for runoff and infiltrate generation (min) was recorded. The weight of sediments collected in the runoff was also recorded at 15 and 30 min. When the runoff volume was <100 mL, the total collected volume was filtered through oven dried, pre-weighed Whatman Number 2 filter paper. When the runoff volume was >100 mL, the total mixture was thoroughly agitated, and a subsample of 100 mL was taken and filtered. The sediment-loaded filter papers were oven dried for 24 h at 105 °C and weighed using a precision balance with a readability of 0.001 g. The sediment concentration in the runoff (SC, g L^{-1}) was calculated using Eq. (3), where M1 is mass of sediment-loaded filter (g), M0 is mass of empty dried filter (g), R: runoff volume (mL).

Table 2
Rainfall characteristics obtained using the Laser Optical Disdrometer.

Median drop diameter [a]	D_{50} (mm)	2.23
Kinetic energy as a function of time	KE_t (J $m^{-2}h^{-1}$)	2332
Kinetic energy as a function of volume	KE_{vol} (J m^{-2} mm^{-1})	26

[a] D_{50} is calculated from cumulative percentage of drop volume.

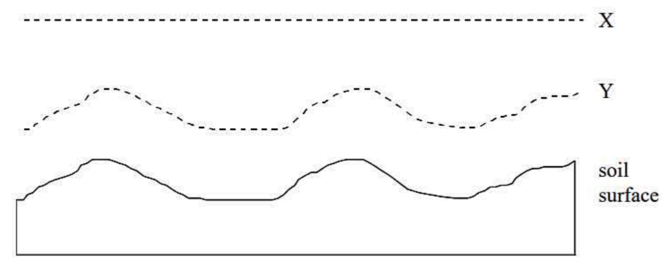

Fig. 2. Representation of a straight-line surface length (X) and a real surface length measured over the soil surface morphology (Y) which gives an indication of the soil surface roughness.

$$SC = \frac{(M1 - M0)}{R} \text{x} 1000 \quad (3)$$

After the rainfall event, infiltration rate was quantified using a mini disk infiltrometer (Decagon Devices, Inc.) which is a tension infiltrometer that measures the hydraulic conductivity of the soil. This measurement will show if differences in the soil surface treatments affect infiltration processes. A suction rate of 2 cm, adequate for most soils, was considered. The water volume (mL) in the infiltrometer tube was recorded over time and the hydraulic conductivity was calculated, based on a method developed by Zhang (1997).

2.3.3. Rainsplash erosion

Splash collectors made from fabric (referred in this paper as "voile") was used to measure detached soil particles by rainsplash. The voiles were suspended over the soil surface, with the lower edge just above the soil surface so not to interfere with surface runoff. The fabric voile was cut into rectangles of 5.5 cm × 9.5 cm and attached to a thread fixed across the width of the tray. For Treatment A, the voile was cut to fit the shape of the ridges and furrows (Fig. 3a).

Two voiles were used per erosion tray, at two different positions, placed at 15 cm from the top and the bottom of the tray (Fig. 3b). For Treatment B, two voiles were both put at 15 cm from the top of the tray, one on the ridge and the other one on the furrow (Fig. 3c).

After the rainfall event, the sediment-loaded voiles were put in pre-weighed tins and oven dried. The detached soil mass is the difference between the weight of tin filled with sediments, with the voile removed, and the empty tin weight (g) and expressed per unit area of the voile.

2.4. Statistical analysis

The experiment contained two blocks. Each block had sixteen erosion trays, that is four replications per treatment, making the whole experiment a total of thirty-two erosion trays (eight replications for each one of the four treatments). The testing sequence for the erosion trays under the rainfall simulator, in each block, was completely randomized. All the data was combined and statistically analysed accordingly, using the statistical software Genstat ® (21st Edition), and the differences in the results data between the treatments were assessed by REML

Fig. 3. Capturing soil particles detached by rainsplash on the erosion trays. (a) Collector voiles cut to fit the shape of Treatment A. (b) Two collector voiles placed at the top and bottom of the erosion tray. (c) Two collector voiles put on the ridge and in the furrow of Treatment B.

(Restricted Maximum Likelihood). This method estimates the treatment effects and variance components in a linear mixed model: that is a linear model with both fixed and random effects. The treatments were assigned to the fixed model, and the random model combined other factors such as the blocks and the order of erosion tests. In addition to that, when significant treatment effects were identified by the REML analysis ($p < 0.05$), the Least Significant Differences (LSD) test was used in order to find out exactly which treatment(s) are different from the others. This test consists in a pairwise comparison of the means with a significance level of 5 %.

3. Results

3.1. Effect of raindrop impact on initial soil surface roughness (SSR)

Table 3 and Fig. 4 present the initial (pre-rainfall) and final (post rainfall) SSR for the different treatments. Before the rainfall event, Treatments A and B had the same degree of surface roughness, but they differed in the orientation of applied roughness. Comparison of mean initial SSR using the least significant differences method (5 % level) showed no significant difference between Treatments A and B. However, the degree of roughness was statistically different between these two treatments and Treatment C ($p < 0.001$), which validates the method used for creating significantly different surface roughness levels to the soil surfaces. Before the rainfall event, the highest initial SSR was measured in Treatment C, followed by both Treatments A and B. These three surface treatments had significantly higher initial soil roughness than the smooth surface.

The final SSR after the rainfall event remained significantly different between the four treatments ($p < 0.001$). Post rainfall, the SSR decreased for Treatments A, B and C, unlike Treatment D where SSR increased after the rainfall event. The REML analysis showed that the final roughness was significantly different from the initial one ($p < 0.001$). The mean comparison using LSD (5 %) showed that this difference is statistically significant for Treatments B, C and D, where the SSR in Treatments B and C decreased by 36 % and 64 %, respectively, and

Table 3
Soil surface roughness (cm m^{-1} or %) for different soil surface treatments, before the rainfall event (initial SSR) and after the rainfall event (final SSR).

Treatments	Surface roughness (cm m^{-1} or %)		SSR change (%) [b]
	Before rain	After rain	
A	16.3	13.8	−15
B	14.7	9.5	−36
C	20.5	7.3	−64
D	2.7	5.8	+113

[b] Negative values indicate a decrease in surface roughness; a positive value indicates an increase in surface roughness.

increased by 113 % for Treatment D. The SSR in Treatment A decreased by 15 %, but this decrease between initial and final SSR is not statistically significant (Fig. 4).

Changes in surface roughness were confirmed by the laser scanner. The scans were processed and analysed for few replications per treatment. For Treatment A, initial SSR was 16.6 % ($n = 2$) and final SSR was 13.8 % ($n = 3$) that is a decrease in roughness by 17 %. For Treatment B, initial SSR was 14.7 % ($n = 2$) and final SSR was 9.1 % ($n = 2$) with a decrease of 39 %. For Treatment C, the roughness decreased by 65 % moving from an initial SSR of 20.4 % ($n = 3$) to a final SSR of 7.1 % ($n = 3$). On the other hand, the initial SSR (3 %, $n = 1$) increased by 95 % for Treatment D with a final roughness of 5.9 % ($n = 1$). These results align with those of the chain method presented in Table 3 and Fig. 4. Images in Fig. 5 show the soil surface roughness of the four treatments before and after the rainfall simulation. For Treatments A and B, before applying the rainfall, it can be observed that each ridge was forming a shadow (dark colour in the image). It is clearly noticed that the light colour gets wider, and the dark shadow gets lighter after applying the rainfall, which indicates the reduction of ridges heights. For Treatment C, it can be observed that the bumps represent the soil clods and aggregates which became smaller after applying the rainfall due to the soil disaggregation. For Treatment D, it is distinctly observed that the soil surface before the rainfall application was smooth. After applying the rainfall, small pits were formed due to the raindrop impact that leads to soil dislocation. This is represented by the contrast of colours (light vs dark).

3.2. Runoff, infiltration, soil loss and sediment concentration

3.2.1. Time-to-runoff and runoff volume

Time-to-runoff is the period between the start of the rainfall and the generation of the first outflow at the runoff outlet. Time-to-runoff (seconds) was recorded for each erosion tray during the rainfall simulations. Treatment C presented the shortest mean time-to-runoff (124 ± 15 s), followed by Treatments D, B and A, where mean time-to-runoff was 166 ± 44, 243 ± 80 and 249 ± 70 s, respectively, from the rainfall start. However, the differences were not significantly different ($p > 0.05$). There was no correlation between the time-to-runoff and the SSR measurements ($r = 0.038$).

Treatment C (random roughness) generated the highest mean runoff volume during the 30-minute rainfall event, generating runoff that was 6.8, 3.8 and 5.0 times the runoff volume for Treatments A, B and C, respectively. REML analysis showed that mean runoff volume was significantly different between treatments ($p < 0.001$). However, the LSDs at the 5 % level show that the difference is only statistically significant between the treatment with the highest mean runoff volume (Treatment C; random roughness) and the other treatments. There is no significant difference between Treatments A, B and D (Fig. 6).

For each treatment, approximately 42 % of the total runoff was

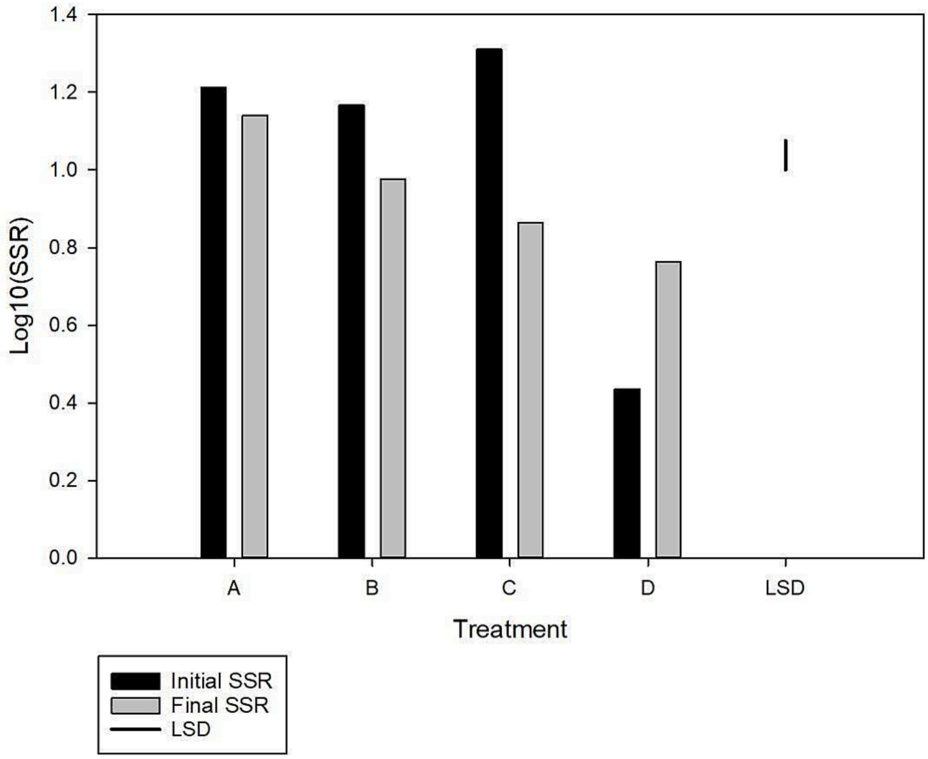

Fig. 4. Soil Surface Roughness (SSR), expressed in Log10, for each of the four treatments measured before (initial) and after (final) the rainfall event.

collected in the first 15 min of the rainfall event and 58 % of the total volume was measured in the latter 15 min of the event. The runoff volume increases with rainfall duration ($p < 0.001$).

After the rainfall event, two contrasting sets of results were identified for Treatment B (across slope SSR): four replicates had lower runoff volumes than Treatments A and D. In this case, the contour ridges of Treatment B behaved as barriers to overland flow, leading to water ponding behind the ridges and less runoff being generated. However, four other replicates presented higher runoff volumes than Treatments A and D.

3.2.2. *Time-to-infiltrate, infiltrate volume and hydraulic conductivity*

Time-to-infiltrate (seconds) is the period between the start of the rainfall and the generation of the first outflow at the infiltrate outlet. This was recorded for each erosion tray during the rainfall simulations. During the experiments, it was observed that infiltrate was always initiated before runoff. The mean time-to-infiltrate ranged from 35 s (Treatment B) to 39 s (Treatment C). Statistical analysis showed that there was no significant difference in time-to-infiltrate between the treatments ($p > 0.05$).

Mean total infiltrate volume (mL) was significantly lower in Treatment C (random SSR) compared to the other treatments (Table 4). For Treatments A, B and C, around 44.5 % of the total infiltrate volume was collected in the first 15 min of the rainfall simulation and 55.5 % was collected in the latter 15 min of the event. This shows that infiltrate volumes increase with rainfall duration. However, for Treatment C, the infiltrate volume slightly decreases over time, with 52.5 % of the volume collected in the first 15 min and 47.5 % in the latter 15 min of the rainfall event.

Similarly, half of the replicates of Treatment B had lower values of infiltrate volume than Treatments A and D, and the other half generated higher values than those two treatments.

Regarding the hydraulic conductivity measured using the mini disc infiltrometer, the statistical analysis showed that there are significant differences between treatments ($p < 0.001$), specifically between Treatment C and all other treatments (according to LSD). Treatment C had the lowest mean hydraulic conductivity (7×10^{-4} cm s^{-1}). On the other hand, Treatments A, B and D had hydraulic conductivity with mean values of 33×10^{-4}, 41×10^{-4}, and 36×10^{-4} cm s^{-1}. These results are consistent in that the lower hydraulic conductivity results in lower infiltrate volume and greater run-off volume.

3.2.3. *Sediment load and concentration in the runoff*

Total soil loss in the runoff (mg) was measured for the four treatments and the difference was statistically highly significant ($p < 0.001$). The mean comparison (LSD) shows that Treatment C had significantly the highest mean total soil loss (Fig. 7a). There was a strong positive correlation between runoff volume and soil loss ($r = 0.85$), as soil particles in the soil mass were both detached and then transported by the runoff.

Similar to the runoff data, half of the replicates of Treatment B had lower values of soil loss than Treatments A and D. The other Treatment B replicates generated higher values of soil loss than Treatments A and D.

Sediment concentration in the runoff (g/L) was also significantly different between treatments and the mean values decrease with rainfall duration by 37, 65, 39 and 69 % for Treatments A, B, C and D respectively (Fig. 7b).

3.3. *Rainsplash erosion*

The significantly lowest mean splash erosion (1.91 mg cm^{-2}) was recorded for Treatment A after 30 min of rainfall. The means of splash erosion for this rainfall duration were 5.2 and 5.9 mg cm^{-2} for Treatments C and D respectively. For Treatment B, splash erosion collected in the furrow was significantly higher than that collected on the ridge ($p < 0.05$), with 8.7 and 3.9 mg cm^{-2} recorded in the furrow and on the ridge respectively.

During the experiment, some additional splash collectors (voiles) were located at the bottom of the erosion tray for Treatments A, C and D. It was postulated that these would catch more splashed material than the

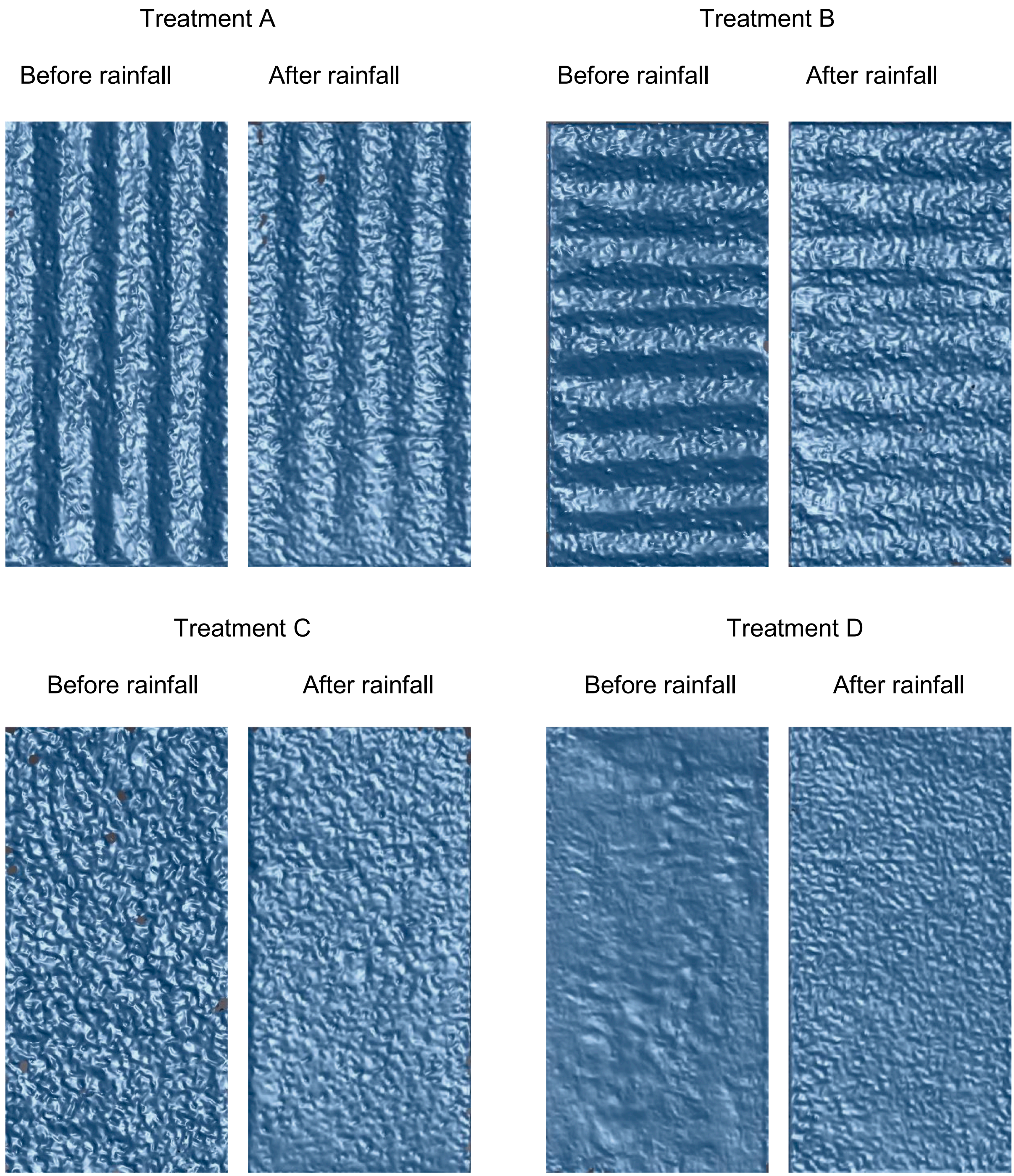

Fig. 5. Changes in the soil surface roughness of the four treatments before and after rainfall simulation. Images from a laser scanner with a resolution of 2 mm. Each image represents the erosion trays' dimensions of 50 × 25 cm.

voiles positioned at the top of the tray, because of the potentially larger catchment area available above the bottom voile, that could contribute detached and transported splashed material. To test this hypothesis, a paired *t*-test was run, and the results show that there was a significant difference between the two locations ($p < 0.05$).

4. Discussion

Soil erosion by water is a result of particle/aggregate detachment from the soil surface followed by the transport of the detached material (Morgan, 2005). These processes are determined by the erosivity of both the rainfall and the overland flow. Kinnell (2005) identified four soil detachment/transport processes: (i) raindrop detachment with transport by raindrop splash; (ii) raindrop detachment with transport by raindrop-induced flow; (iii) raindrop detachment with transport by overland flow, and (iv) detachment and transport by overland flow. However, rain-splash is considered the most important detaching agent (Morgan, 2005) as a result of the relatively high raindrop energies impacting the soil surface. It is also considered the initial phase of the erosion process (Kinnell, 2005).

4.1. *Effect of raindrop impact on initial SSR*

Zhao and Wu (2015) suggested that the morphology of a soil surface

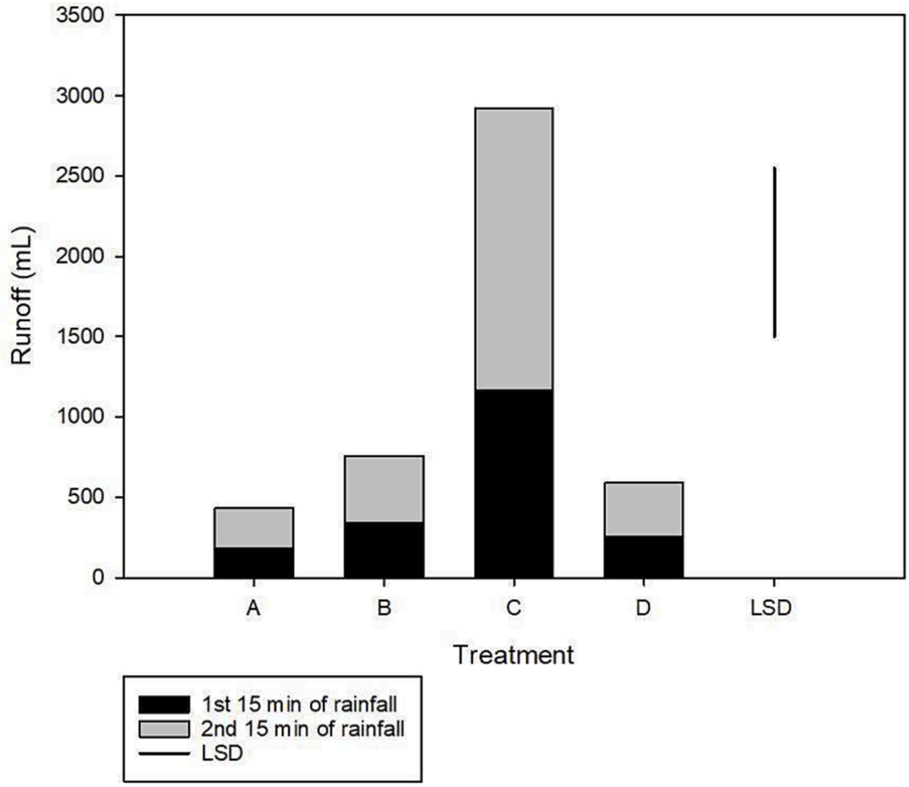

Fig. 6. Mean runoff volumes (mL) generated by the four surface treatments during a 30-minute rainfall event. LSD was used to compare between means of the 30 min data.

Table 4
Mean infiltrate volumes (mL) from the four surface treatments during the 15-minute and 30-minute rainfall event.

Treatments	Infiltrate (mL)	
	1st 15-min event	2nd 15-min event
A	2950	3381
B	2606	3313
C	2024*	1833*
D	2656	3546

* The difference between Treatment C and the other treatments is statistically significant. LSD values for the 1st and the 2nd 15 min data are 530 and 584 mL, respectively.

changed significantly after rainfall. Increases or decreases in soil surface roughness (SSR) after exposure to rainfall depend mainly on the original condition of the soil surface (Govers et al., 2000). This was also presented by Huang and Bradford (1992), Magunda et al. (1997) and Zhao et al. (2014a). According to a number of previous studies, rainfall decreases SSR for initially rough soil surfaces, while it increases the roughness of the initially smooth surface. Zhao et al. (2014a) noticed that an initially smooth surface developed many discrete crescent-shaped pits following rainfall and related the increase in SSR to the shear force of overland flow. Huang and Bradford (1992) found that increased rainfall amount caused the development of micro-rills leading to a higher surface roughness. Römkens et al. (2001) also found that an initially smooth surface became rougher due to rill development and flow incisions. The results of the present study however show that raindrop impacts cause soil particles to be dislodged, transported in the rainsplash jets and redeposited elsewhere on the soil surface (Bullard et al., 2018a). This process generates microrelief in the initially smooth surface, leading to an increase in the surface roughness, post rainfall (Treatment D in Fig. 5).

Regarding the rough surfaces, our results showed a decrease in SSR of 15 % for the up/down-slope roughness (Treatment A) and 36 % for the across-slope roughness (Treatment B). Even though their initial surfaces had the same degree of roughness before the rainfall event, the decrease in surface roughness after the rainfall event was greater in Treatment B than in Treatment A. This is because of the contrasting results between replicates observed for Treatment B (discussed later). The average between the two mean values aligns with the results found by da Rocha Junior et al. (2016), who demonstrated a tendency of SSR to decrease after the rainfall event by 22.7 % in contour tillage and up/down-slope tillage treatments. The decrease in soil roughness is due to the kinetic energy of raindrops that break down soil aggregates (Kinnell, 2005) and larger surface structures such as ridges. The detached material is then transported from the microtopographic elevations and deposited in small, local depressions (Kirkby, 2001; Zhao et al., 2019). The local elevations and depressions in Treatment C were not as marked (i.e. high and deep respectively), as the ridges and furrows of Treatments A and B. Therefore, the aggregates in Treatment C were rapidly broken down and deposited in local low spots which makes this treatment the one with the highest relative surface roughness decay after the rainfall event, as mentioned in the results section.

4.2. Runoff, infiltration, soil loss and sediment concentration

The random roughness treatment (Treatment C) generated significantly more runoff and soil loss than the other treatments. The soil aggregates were rapidly broken down under the energy of the raindrops hitting the surface, and the water flow rapidly filled the small depressions of the rough surface. Any additional water was then routed between the dispersed aggregates and it entrained the resulting disaggregated, detached material and transported it downslope (Bullard et al., 2018b; Darboux et al., 2004; Helming et al., 1998; Römkens et al., 2001). This treatment presented the shortest time-to-runoff. However, the difference between treatments was not significant, mainly because

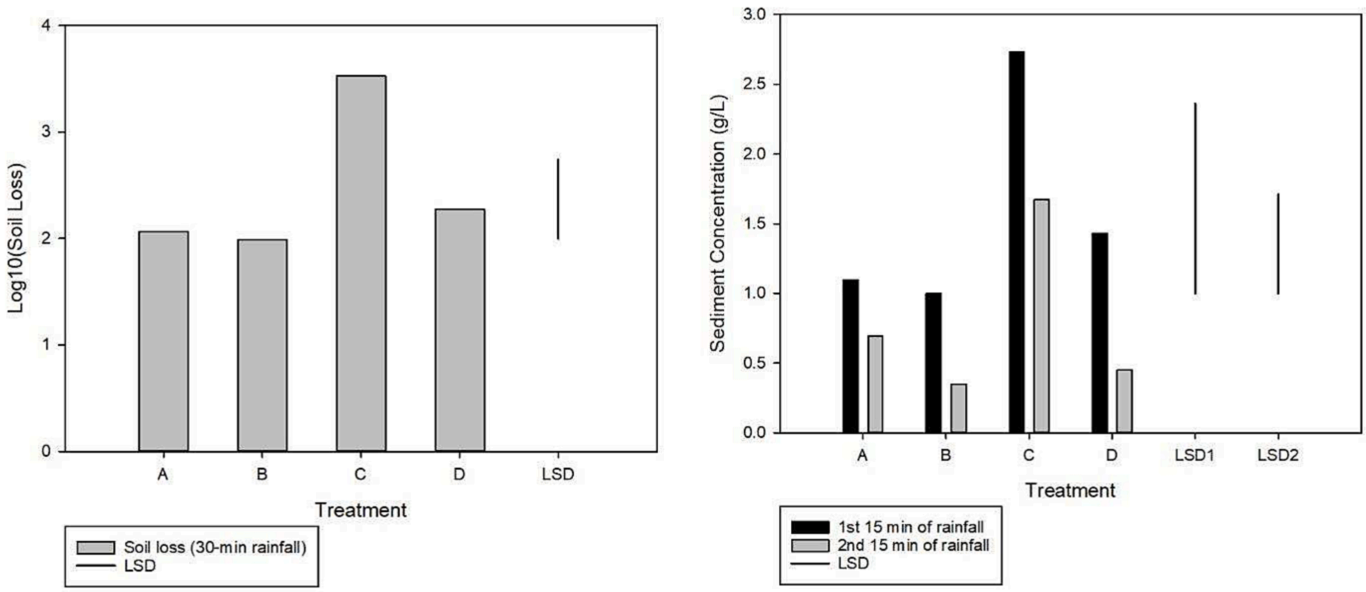

Fig. 7. (a) Mean total soil loss (mg), expressed in Log10, generated during a 30-minute rainfall event. LSD was used to compare between the means. (b) Mean sediment concentration in the runoff (g/L) collected after the first 15 min and the second 15 min of the rainfall event. LSD1 was used to compare between means of the 1st 15 min data, and LSD2 for means of the 2nd 15 min data.

the soil was initially wetted to the same moisture content for all treatments before the rainfall event. Also, the rainfall intensity used (90 mm hr^{-1}) was relatively high which hastened runoff generation, so masking any potential, more nuanced difference between treatments. According to Darboux et al. (2004), using excessive rainfall events, there was no difference in the runoff delay between initially rough and smooth surfaces.

As a result of more breakdown of aggregates in Treatment C, a surface seal was formed in some places, particularly in the depressions where raindrop impact compacts the soil. The formation of seals can reduce rates of infiltration and increase surface runoff and soil loss (Bullard et al., 2018a). This explains, compared to the other treatments, the markedly high runoff volume, low infiltrate volume and low infiltration rate, generated by the random roughness treatment (Treatment C). The infiltration rate for this treatment (7×10^{-4} cm s^{-1}) was lower than the rainfall rate (25×10^{-4} cm s^{-1}), and according to the hydrological basis of erosion, if the infiltration rate is less than the rainfall intensity, then runoff will be generated (Morgan et al., 1998). Also, the present results showed that runoff increased with rainfall duration, and for Treatment C the infiltrate volume decreased with rainfall duration. Zhang et al. (2016) explained that this phenomenon is due to a) the saturation of soil as the rainfall duration increases, and b) the formation of a surface seal over time that would also reduce infiltration.

Sediment concentration in the runoff decreased with rainfall duration from 15 to 30 min for all four soil treatments. This can be explained by the availability of loose, easily eroded material during the first minutes of the rainfall event. Once this has been washed away, the erosion rate declines, as only less erodible material remains on the soil surface (Arshad et al., 2019; Cao et al., 2013).

In general, the literature states that across-slope cultivations perpendicular to the slope fall line create a physical impediment to the downslope movement of water. This would result in less runoff and soil loss in comparison with soil tilled up and down the slope (da Rocha Junior et al., 2016; da Rocha Junior et al., 2018; Luciano et al., 2009). This is the basis of the present study's hypothesis. Indeed, for four replicates of Treatment B, runoff and soil losses were lower than for Treatments A and D. Furthermore, furrows in Treatment A acted like canals that routed the water flow downslope. However, contradictory results were recorded for four other replicates of Treatment B, where higher runoff and soil losses were recorded than for Treatments A and D. This is because the elevation of some ridges was lowered by soil detachment due to raindrop impact, allowing any previously ponded water in the furrows to breach the ridges in concentrated flow paths. So, the ridges were damaged not only by raindrop impact, but also by overland flow coming from ponded water in the furrow, generating more runoff and soil loss. Fig. 8 shows the case were the ridges maintained their shape versus the flattened ridges further downslope, where resistance to flow decreases (Parsons et al., 1990) due to the cumulative concentrated water upslope that broke down the ridges, along with breakdown due to rainfall impact. The difference between these two contrasting results for the same treatment was significant and measurements of the replicates' final surface roughness confirmed it. On the other hand, the furrows in Treatment A were oriented in the up/downslope direction, which means that there was no ponded water behind the ridges that would lead to an increase in runoff volume. For these reasons, and given that in some cases Treatments B generated more runoff and soil loss than Treatment A, and in other cases it generated less, the mean runoff and soil loss values for both treatments

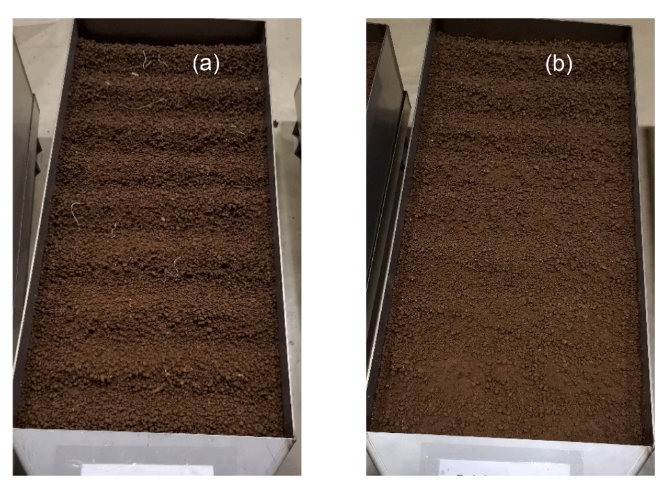

Fig. 8. Post rainfall images for Treatment B (across slope SSR). (a) Ridges not flattened, intact. (b) Ridges flattened, especially downslope, near the runoff outlet.

were not significantly different, and soil loss results found by Quinton and Catt (2004) on plots with different roughness orientations suggest a similar conclusion.

Although across-slope contour cultivation is assumed to be an effective soil and water conservation measure (da Rocha Junior et al., 2018), it is less effective on slopes exceeding 10 percent (USDA, 2017; Alvarez-Mozos et al., 2011). Quinton and Catt (2004) recommended that this management practice should be evaluated at the field scale and on different slope configurations, as it could be a risk on complex, multidirectional slopes where cultivations are difficult to keep exactly on the contour, leading to low spots along the cultivation row. Water would accumulate in these low points and then break through the ridges to form concentrated flow paths with sufficient flow volume, velocity and kinetic energy to detach and transport material. This process also relates to the difference in surface storage capacity between a gentle and a steep slope gradient. The steeper the slope, the smaller the surface storage capacity (Zhao et al., 2021). Once filled, any subsequent rainfall event will cause overtopping of the storage, leading to water breaching the ridges and causing a risk of erosion (Morgan, 1992).

Even though da Rocha Junior et al. (2016) reported lower values of runoff for a contour tillage treatment, this was only under a simulated rainfall intensity of 50.8 mm hr^{-1}. However, when increasing the rainfall intensity to 114.3 mm hr^{-1}, contour tillage presented higher values of runoff, along with the bare soil treatment. This was explained by the possible partial breaking of ridges due to the kinetic energy of the higher rainfall intensity applied.

On the other hand, a high rainfall intensity and/or a steep slope gradient might result in the reduced effectiveness of across-slope contour tillage in controlling soil and water losses. In the present study, the rainfall intensity used was of 90 mm hr^{-1}, a value which is between the low and the high intensity values used by da Rocha Junior et al. (2016). Also, the present study used a slope gradient of 10 % which is the limit for effective control of soil and water losses by contour tillage (USDA, 2017). This suggests unclear conclusions regarding the effectiveness of across slope soil and water management practices (such as contour cultivations, buffer strips and earth bunds) as demonstrated by the contrasting observations discussed in this paper. More research should be done on this topic, simulating a range of rainfall intensities and slope gradients.

4.3. Rainsplash erosion

The hypothesis was that Treatment C (random roughness) would produce more splash erosion than the other treatments because the roughness elements were created by disturbing relatively wet soil, breaking up any initial aggregation and making the soil particles more prone to detachment (Torri et al., 1987). However, the highest splash soil loss was in Treatment B (the across-slope oriented roughness). Even so, the results show no significant difference in splashed soil loss between Treatments B, C and D. This is supported by Morgan (2005), who found that surface roughness has no control over soil detachment by rainsplash.

Although not statistically significant, the mean splash erosion for the smooth surface (Treatment D) was slightly higher than for the rough surface (Treatment C). This is explained by the rough surface of Treatment C intercepting some of the splashed material in micro-depressions. Also, it was observed that there was a thin water layer on the surface of Treatment C during the rainfall event, especially ponding in the micro-depressions, which might have buffered against splash impacts. Hairsine et al. (1992), Kinnell (2005) and Torri et al. (1987) claimed that raindrop kinetic energy is absorbed by water films, leaving less energy available for soil detachment. However, this contradicts Palmer (1964) and Moss and Green (1983) who found the relationship depends on the size of the impacting drops, relative to the depth of the water film.

For Treatment B (the across-slope oriented roughness), the splashed material collected from the voiles put in the furrows was greater than that captured on the ridges, because the detached particles from relatively higher elevations (i.e. ridges) were moved by gravity and deposited at lower elevations (i.e. in the furrows) (Zhao et al., 2014b). Bullard et al. (2018b) suggested that with increasing range in surface elevation, rates of rainsplash erosion also increase. This explains the higher splash erosion recorded for Treatment B than for Treatment C which has a smaller elevation range than the former treatment. Similarly, Luo et al. (2018) found that soils subject to ridging practices had higher soil detachment rates than other rough surfaces, because more soil surface area was exposed to the raindrops due to the presence of the ridges and furrows. In the same way, Wu et al. (2016) claimed that microrelief (e.g. ridges and furrows), increased local slope gradients and hence increased detachment rates due to increased raindrop impact associated with the slope increase. The opposite was found by Zhao et al. (2014b), explaining that the microrelief increased the area and the local slope of the surface, resulting in decreased rainsplash erosion, as the raindrop impacts were spread over a larger area. This can explain the results found for Treatment A (up- and downslope oriented roughness) which also contains ridges and furrows but presented significantly lower values of splashed sediment than the other three treatments. This could also be explained by the way the splashed sediment was captured, as the voile collectors were put perpendicular to the ridges and furrows (Fig. 3a), unlike Treatment B. These results align with the earlier findings related to changes in SSR, where the decrease in soil surface roughness of Treatment B was the smallest.

Understanding the different mechanics of rainsplash erosion on smooth or rough soil surfaces is complex. Splash erosion is dependent on surface microtopography and is sensitive to small changes in soil properties, including soil surface relief (Zumr et al., 2020). Measurement of rainsplash erosion is strongly dependent on the collection method (Fernández-Raga et al., 2019). Although falling raindrops might have an effect on the particles previously captured in the collection method we used in this study, this effect applied to all experimental runs, trays and treatments, so the measurements are consistent between all trays.

Comparing the rainsplash results from the upslope and downslope position on the erosion trays shows that for all the treatments, the splashed soil captured at the downslope position was higher than that captured further upslope. This is explained by the larger catchment area above the downslope voile, allowing more detached particles to be transported and captured from the whole length of the erosion tray. On sloping land, particles splashed downslope travel further due to gravity than particles splashed upslope, resulting in net downslope splash erosion (Kinnell, 2005; Morgan, 2005; Wan et al., 1996; White, 2006). This aligns with the findings of Wu et al. (2016) who used a splash board to catch detached particles (upslope and downslope) on slopes with different soil microreliefs and found a positive net downslope movement of splashed material on a smooth soil surface. However, for other cultivation treatments (shallow hoeing, contour chisel ploughing), they found lower and even negative net values for splash erosion because of the spatial microrelief structure so that the net movement of the splashed material wasn't necessary downslope.

5. Conclusions

The experimental conditions in this study were designed to evaluate the effect of soil roughness and orientation on soil and water losses. The study is unique in comparing random roughness and oriented roughness, with both up/downslope and across-slope orientations, in terms of simultaneous generation of runoff, infiltration, soil loss and splash erosion. The study showed that rainfall affected the soil surface of the sandy loam soil by increasing or decreasing its roughness. Smooth surfaces became rougher after dislocation of soil particles due to raindrop impacts, whereas on rougher surfaces, surface roughness degraded after the rainfall event, due to the kinetic energy of raindrops breaking down ridges and soil aggregates. This study concluded that random roughness generated significantly more runoff and soil loss and less infiltration than smooth or oriented roughness treatments.

Our results show that across-slope oriented roughness does not always give better runoff and erosion control compared with up/down slope cultivations as mentioned in the literature. The contradictory results from the treatment replicates can be explained in part by previous research that showed across-slope cultivation is less effective on slope gradients exceeding 10 % (the slope gradient used in the current study was exactly 10 %). This suggests more research is needed to observe these effects at different slope gradients as the outcomes may be sensitive to slope gradient.

Even under controlled experimental conditions, the effect of soil surface roughness on splash erosion is complex and the mechanisms operating are not clear. This justifies further experimental work to generate better understanding of the processes at work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The underlying data can be accessed through 10.17862/cranfield.rd.21829884

Acknowledgments

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