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Impact of mulching on soil and water dynamics under intermittent simulated rainfall

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ABSTRACT

Application of crop residues to soil is a common management practice for soil erosion control and for improving rainfall infiltration. Runoff generation, sediment transport and soil water storage are complex phenomena, involving several interdependent processes. Antecedent moisture conditions, rainfall patterns, and soil cover play an important role in the detachment and transport of soil particles and infiltration. This study aimed to investigate in laboratory the effect of distinct mulch densities on runoff and sediment transport, by using multiple step intermittent rainfall events. Laboratory experiments were conducted using a soil flume and rainfall simulator with three soil cover treatments: 1) bare soil; 2) low mulch cover, 2 t/ha density; and 3) high mulch cover, 4 t/ha density. Experiments comprised a sequence of five different rainfall events in an intermittent way, i.e., three uniform patterns with increasing rainfall intensities, one advanced pattern and one delayed pattern. The laboratory experiments described in this work clearly show that mulching strongly affects infiltration, soil moisture, surface runoff and erosion. Intermittency and characteristics of sequential rainfall events also influenced these processes. Experimental results showed that mulch covers of 2 t/ha and 4 t/ha caused reductions of, respectively, 21% and 51% in the runoff peak. High mulch cover rates resulted in a significant increase in soil moisture. Additionally, soil temperature was more optimally regulated under a mulch cover density of 4 t/ha.

1. Introduction

Erosion by water is the result of the interaction of climate, surface runoff, soil, topography, vegetative cover, soil management and conservation practices, and manifests itself as varying in time and space on the ground surface. Losses of soil and nutrients and their subsequent transport by water are primarily responsible for farmland degradation, leading to a decline in the land productive capacity and eventually to the unsustainability of agricultural production systems (e.g., Oliveira et al., 2010).

Runoff and sediment transport are complex hydrological phenomena. Antecedent soil moisture conditions, soil cover and rainfall intensity play an important role in the rainfall-runoff process and the resulting water and soil losses (e.g., Römkens et al., 2001). The temporal variability of rainfall has a large impact on runoff generation and associated transport processes (e.g., de Lima et al., 2009; Mannaertsa and Gabriels, 2000), particularly in semiarid areas where transport by storm events spans different orders of magnitude (e.g. de Lima and Grasman, 1999; de Lima et al., 2002).

Many researchers have highlighted the importance of the combined effect of rain and wind on the soil transport process (e.g., Erpul et al., 2002, 2003, 2004; Fister et al., 2011; Ries et al., 2009), which also depends on the characteristics of soil texture, structure and grain size distribution. The main factors to be taken into consideration in rainfall simulation are the experimental area and the intensity and duration of rain (e.g., de Lima and Singh, 2003; de Lima et al., 2012; Marques et al., 2007), both of which are highly variable in time. Truman et al. (2007) noted that more changes usually occur at the soil surface when variable rainfall intensity patterns are applied, as compared to uniform precipitation. Deng et al. (2008) carried out laboratory experiments and numerical modeling to investigate the hydrograph shape for overland flow and sediment transport produced by simulated rainfall with varying intensities. Carvalho et al. (2009) studied the relation between rainfall erosivity, rainfall pattern and erosion losses associated with different types of soil preparation and cover in a red yellow argisol. They found that the precipitation events characterized as advanced, intermediate and delayed patterns were responsible, respectively, for 62.6%, 11.8% and 25.6% of the water losses and for 35.1%, 6.6% and

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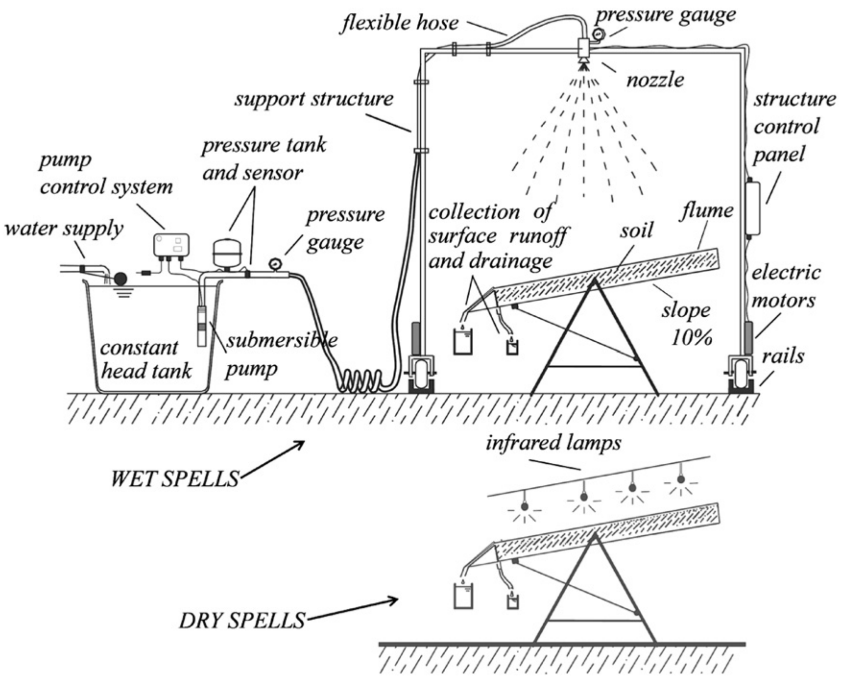

Fig. 1. Laboratory setup used during rainfall events (top) and dry spells (bottom).

58.3% of the soil losses. Ran et al. (2012) observed that rainfall intensity patterns and duration are two relevant factors controlling hydrological response of a basin, affecting overland flow and sediment transport. Peak intensities can occur at any moment during a rainfall event. Zhang et al. (1997) classified rainfall according to the relative peak position as advanced peak, intermediate peak, and delayed peak rainfall. When analyzing the importance of intensity fluctuations within a single rainfall event, early peak rainfall patterns tend to produce higher runoff peaks than uniform rainfall events and time varying late peak events are usually associated with the highest runoff peaks and soil losses for the same initial conditions (e.g., Dunkerley, 2011; Xue and Gavin, 2008).

In experiments using varying patterns in rainfall simulator to investigate agrochemical transport, Zhang et al. (1997) verified that advanced single peak events produced significantly higher dissolved herbicide losses than delayed single peak events, although runoff volumes were not different among the adopted rainfall patterns. They observed that higher sediment amounts and runoff were produced by the delayed rainfall patterns. Römkens et al. (2001) showed that a sequence of rainfall events of decreasing intensity caused more soil loss than a similar symmetrical sequence with increasing intensity. Focusing on the impact of rainfall storm movement across the catchment, de Lima et al. (2003, 2009) observed that downstream moving storms produced higher soil loss than upstream moving storms. Comparison among the effects of advanced, centered and delayed single peak rainfall patterns on runoff and sediment transport was also performed by de Lima et al. (2012). A systematic study by Ran et al. (2012) investigated the relative importance of pattern characteristics for soil losses, runoff peaks and sediment concentration. They also analyzed the relevance of rainfall moving storms of overland flow generation, as previously addressed by de Lima and Singh (2002, 2003). A set of rainfall events with different durations and no rainfall intervals, comprising a first event with soil in initially dry condition, hence adopting multiple peak intermittent rainfall patterns, was analyzed by Ran et al. (2012). Sediment concentration in the first event was higher than that in the following events, as more erodible particles were present. When initial soil moisture was higher, the runoff start time occurred earlier, with higher runoff peaks being observed. The effect of continuous and intermittent rainfall events was also studied in laboratory by Fohrer et al. (1999), with two initial moisture conditions. They showed that initial dry conditions presented more changes in microrelief than the moist experiments, both in the continuous and the intermittent rainfall regimes. Changes in surface roughness could have an influence on overland flow velocity and transport capacity, in terms of reducing them. On the other hand, this effect can be compensated for by the higher compaction shown in dry conditions and thus an increase in shear strength of the soil surface layer. Notwithstanding the large number of experimental studies using rainfall simulators, little is still known about the relevance of rainfall patterns, particularly considering temporary cessation of rainfall, under distinct soil cover treatments, and when adopting soil conservation methods.

It is generally recognized that mulching and rainfall intensity have a significant impact on soil erosion and that an interaction exists between

Table 1
Main physical and chemical characteristics of the water used in the experiments.

Parameters	Units	Minimum	Maximum
Temperature	°C	13	15
Conductivity	μS/cm	92	128
pH	–	6.6	7.9
Turbidity	NTU	<0.3	5.9
O_2	mg/L	<0.5	2.4
Total hardness	mg $CaCO_3$/L	26.2	41
Total organic carbon	mg C/L	1.3	2

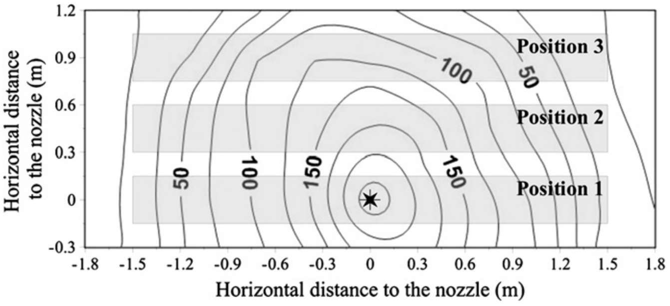

Fig. 2. Spatial distribution of rainfall intensity at the flume level (isohyets in mm/h), with representation of the flume in the three adopted positions relative to the nozzle. The symbol ✳ represents the location of the vertical that contains the nozzle.

the percentage cover and rainfall intensity on sediment/nutrient losses (e.g., Jin et al., 2009). Several investigations on the impact of mulching on runoff have been conducted, addressing the effect of cover densities on surface flow, soil moisture and soil temperature (e.g., Cook et al., 2006). However, quantifying such impacts for rainfall intensities and durations and for intermittent sequences of rainfall events has not been fully addressed. Jin et al. (2009) analyzed the effect of three uniform rainfall intensities, independently applied to four cover percentages on runoff and sediment transport. Sediment loss was positively correlated to rainfall intensities, whereas lower cover produced higher erosion. Moreover, under a rainfall intensity of 65 mm/h, low mulch of 25% cover produced higher soil loss than bare soil.

Jordán et al. (2010) showed that long term mulching application improved physical and chemical properties of a semiarid soil in Spain. Increase in rainfall interception, delay in runoff generation, and reduction in runoff and sediment yield were investigated under a mulch cover density of 5 t/ha × year. An important aspect highlighted by the authors was the exhaustion of available erodible particles after storms longer than 30 min, thus reducing sediment transport. Zonta et al. (2012) evaluated the influence of successively repeated precipitation patterns, applied to bare and covered soils, to quantify their effect on the formation of soil crust and, consequently, on soil water infiltration rate. The authors found that comparing the infiltration rate curves with the tests in soil, with and without vegetation, the infiltration rate on the uncovered soil was much smaller than in the covered condition, especially for the second and third applications. On trials without vegetation cover, with consecutive applications, the infiltration rate decreased significantly over time. For the tests with vegetation cover, when there was decreasing permeability rate over time, infiltration was less abrupt, and for the second rainfall application practically all precipitated water infiltrated into the soil profile.

Mulching is relevant for soil physical amelioration, soil temperature control, and water conservation. Conversely mulching can adversely increase rainfall interception, when mulching thickness and cover density is too high. So, it is expected that the type and cover density of mulch would have distinct influences, depending on the crop stage, soil type, and climate conditions. Lal (1976) adopted 4–6 t/ha straw mulching in semiarid Nigeria and found that soil physical properties were improved. In England, Cook et al. (2006) observed under natural rainfall that wheat straw from 2 to 8 t/ha positively regulated the temperature of topsoil and enhanced soil moisture. Also under natural rainfall in a semi-arid watershed in northeast Brazil, Santos et al. (2010) noted that the surface condition significantly influenced the soil moisture content variation both in dry and rainy seasons. The use of 3.2 t/ha bean straw as mulch, associated with rock barriers, provided high soil moisture levels and increased bean production. Souza et al. (2011) adopted 9 t/ha bean straw as mulching in a highly heterogeneous alluvial valley in northeast Brazil, with controlled micro sprinkler irrigation depths. Mulching proved to be efficient in retaining soil moisture and reducing the variation coefficient, thus decreasing soil moisture spatial variability. In addition, higher temporal dependence along the entire crop cycle was obtained. Adopting a uniform rainfall profile and four different cover indexes, Pan and Shangguan (2006) evaluated the influence of grass on soil erosion. It was shown that sediment yield rate of grass plots decreased with rainfall duration, and decreased linearly as runoff rate increased.

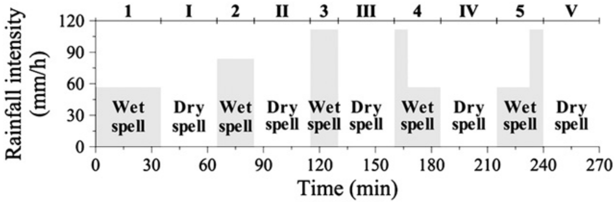

Fig. 3. Multiple-step intermittent rainfall events used in the laboratory experiments (see also Table 3).

In nature, it is necessary to recognize that many natural rainfall events present some degree of intermittency. Thus, studies focusing on runoff and soil sediment as a result of intermittent rainfall for different soil cover conditions are still required. The objective of this study was therefore to investigate the effect of distinct mulch densities on runoff and sediment transport, considering a multiple step intermittent rainfall procedure, comprising not only uniform rainfall events but also an advanced event followed by a symmetrical delayed rainfall profile event. This is a key aspect of this paper. The study is expected to also provide insights into the role of mulching and rainfall characteristics on soil moisture and alternatives for better management of agricultural lands. Results should enhance our understanding of rainfall-runoff processes and soil stability when different soil cover conditions occur as in semiarid areas.

2. Materials and methods

2.1. Laboratorial setup

Laboratory experiments were conducted using a soil flume and a rainfall simulator. Fig. 1 presents a sketch of the experimental set up used during rainfall events and dry spells. The free drainage rectangular soil flume (Fig. 1) consists of metal sheets, 3.0 m long, 0.3 m wide and 0.12 m deep. Tests were carried out for a 10% slope gradient.

Table 2

Characteristics of the simulated rainfall for the three defined positions (see also Fig. 2). The uniformity coefficient was calculated according to Christiansen (1942). The values of raindrop diameters and velocities were calculated from measurements with a Laser precipitation monitor-distrometer (ThiesClima®) during the three rainfall intensities, in three places on the soil flume surface (middle, top and bottom).

	Units	Flume positions		
		1	2	3
Horizontal distance to the nozzle along the rails	m	0.90	0.45	0
Mean rainfall intensity	mm/h	57	84	112
Maximum	mm/h	118	176	243
Minimum	mm/h	2	7	11
Uniformity coefficient	%	37.3	43.7	47.1
Mean raindrop diameter	mm	0.77	0.77	0.70
Mean drop velocity	m/s	2.8	2.58	2.59

Table 3

Characteristics of both rainfall events and dry spells used in the experimental procedure (see also Fig. 3).

Event number		Type of event	Duration of event (min)	Rainfall rate (mm/h)
Wet	Dry			
1		Uniform pattern	35	57
	I	Dry spell	30	–
2		Uniform pattern	20	84
	II	Dry spell	30	–
3		Uniform pattern	15	112
	III	Dry spell	30	–
4		Advanced pattern	25 (7.5 + 17.5)	112/57
	IV	Dry spell	30	–
5		Delayed pattern	25 (17.5 + 7.5)	57/112
	V	Dry spell	30	–

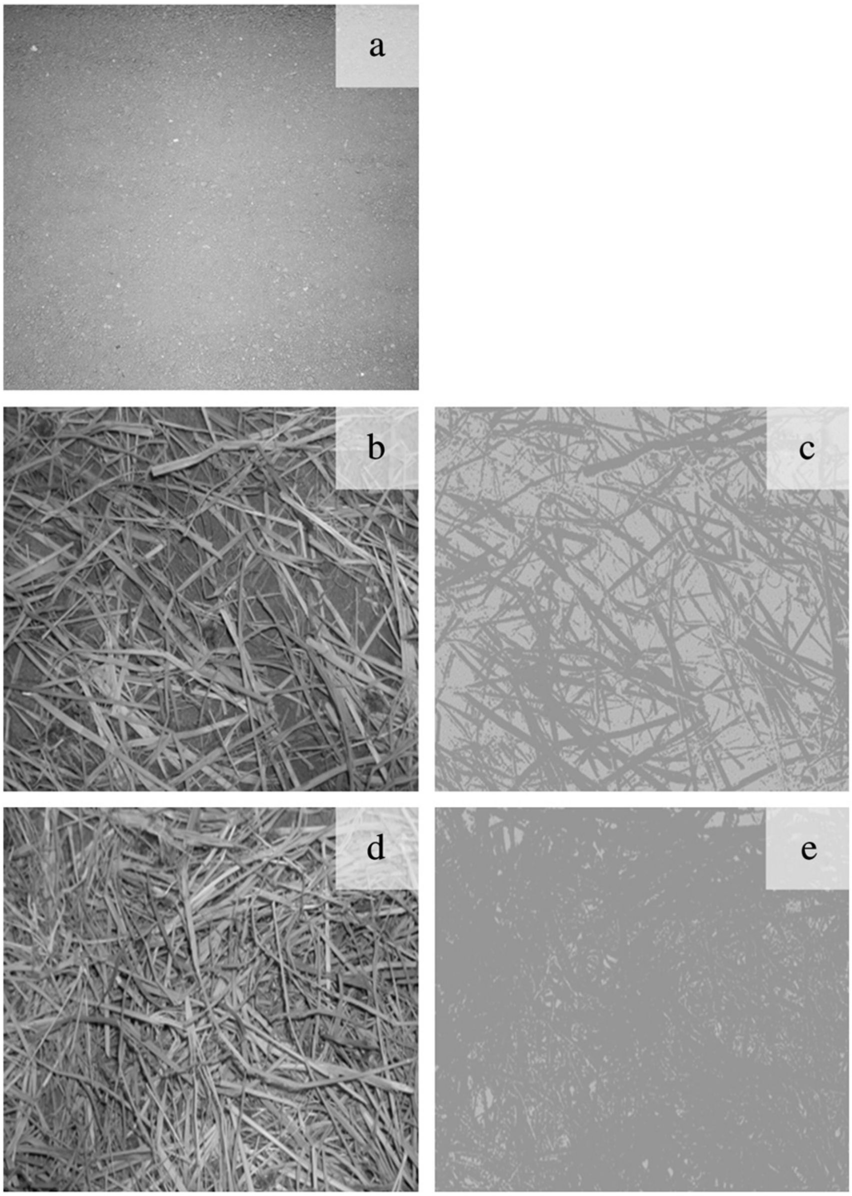

Fig. 4. Soil flume surface photographs: a) bare soil, b) low mulch cover and c) high mulch cover. Imagery analysis using Spring Software: d) low mulch cover and e) high mulch cover.

2.1.1. Soil

A sandy-loam soil from the right bank of River Mondego, in Coimbra, Portugal (de Lima et al., 2003), was used in the experiments. The soil fraction comprised 7% clay, 9% silt, and 84% sand, with gravel fraction of quartz, feldspars, quartzite, muscovite and clay minerals (using standard methods: laser diffraction particle size analyzer for particles finer than 0.25 mm and conventional sieving for particles larger than 0.25 mm). Standard laboratory permeability tests estimated saturated hydraulic conductivity as 5.7×10^{-5} m/s, with a standard deviation of 1.8×10^{-5} m/s.

The air dried pre-sieved soil was manually spread along the flume and compacted to reproduce a natural bulk density of 1340 kg/m^3. A sharp straight-edged blade was used to produce a plane top surface and a soil layer with a uniform thickness of 0.1 m, adjusting the soil to match the retained bar at the bottom end of the flume. In order to ensure identical initial conditions in the beginning of each sequence of intermittent rainfall events, the soil in the flume was removed and then replaced with fresh soil following established protocol. In this way, initial soil moisture, soil compaction and soil surface roughness were the same before the start of each run.

2.1.2. Rainfall simulator

The rainfall simulator utilized has a steady single downward-oriented full-cone nozzle, (3/8 HH FullJet from Spraying Systems Co), with an orifice diameter of 4.8 mm, positioned 2.25 m above the geometric center of the soil flume surface and with a spray angle of 90º. A submerged pump (76.2 mm SQ Grundfos Holding A/S.), installed in a constant head reservoir and an electric retention valve allowed a steady operating pressure of 1.4 bar at the nozzle. The nozzle was supported by an electrically movable metal structure that allows a unidirectional movement of the nozzle along a pair of rails. City water was used for the rainfall simulator and had characteristics as shown in Table 1.

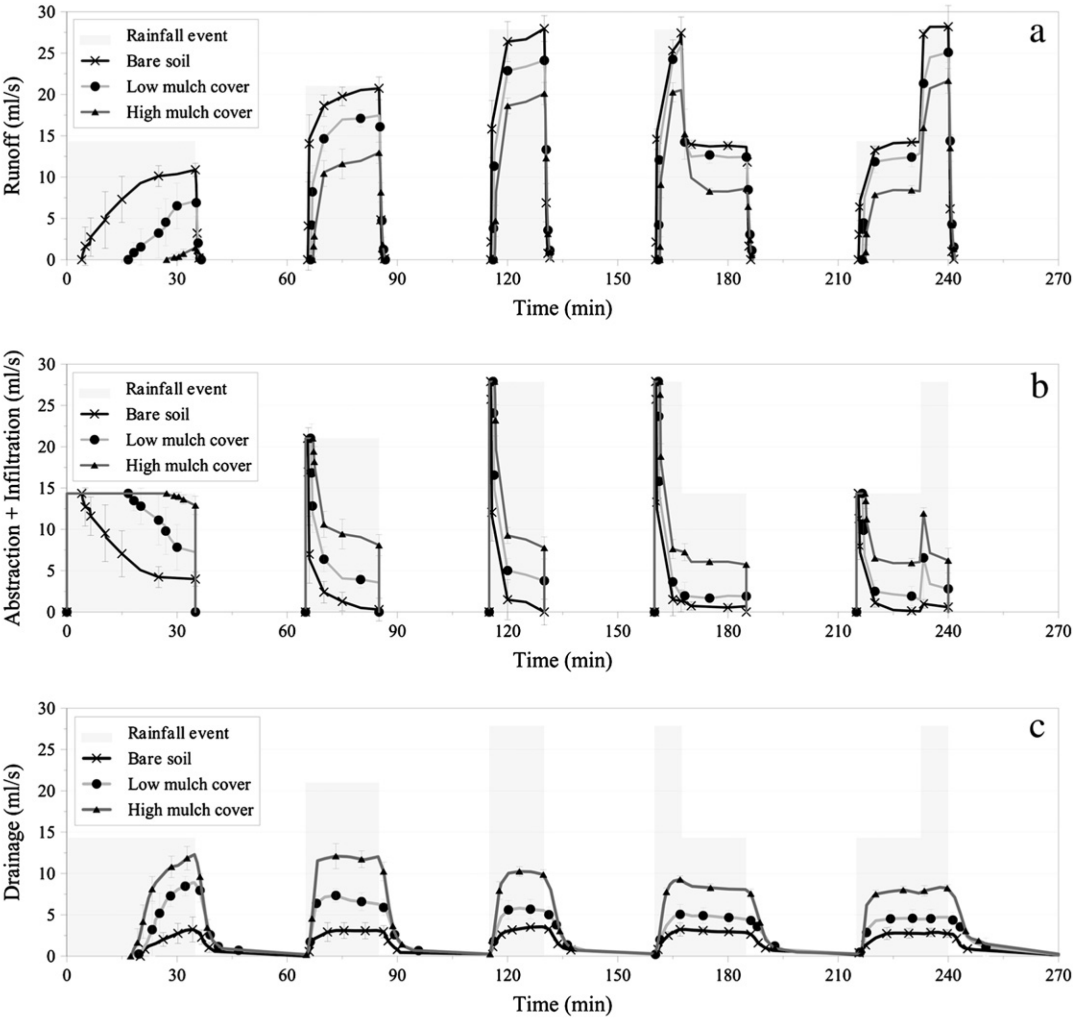

Fig. 5. Results related to measured flows: a) runoff; b) infiltration plus abstraction; and c) drainage. Average and standard deviation bars of the three repetitions.

2.2. Rainfall simulations

A total of 45 rainfall events (3 repetitions of sequences of 5 rainfall events for 3 soil cover treatments) were carried out. In order to obtain different rainfall intensities, three positions were defined by lateral distances between the spraying nozzle and the flume's geometrical center (positions 1, 2 and 3). This was achieved by moving back and forth the support structure of the nozzle, using the two electrical

Table 4
Parameters related to major flows obtained from the graphics of Fig. 5. Average values and standard deviation (between brackets) of the three repetitions.

Soil cover treatment	Rainfall event	Runoff peak (ml/s)	Time to runoff (min)	Total precipitated volume (l)	Total runoff volume (l)	Total infiltrated volume (l)	Total drained volume (l)
Bare soil	1	11.0 (0.6)	6.9 (2.6)	30	14.8 (3.2)	15.1 (3.2)	2.5 (1.0)
	2	21.1 (1.8)	0.7 (0.1)	25	22.6 (1.8)	2.6 (1.8)	3.9 (1.2)
	3	28.0 (1.6)	0.5 (0.0)	25	22.4 (1.8)	2.8 (1.8)	3.4 (0.1)
	4	27.8 (1.6)	0.4 (0.0)	28	24.5 (0.9)	3.0 (0.9)	4.8 (0.7)
	5	29.0 (2.0)	0.6 (0.1)	28	25.9 (0.8)	1.7 (0.8)	4.3 (0.9)
			Total	136	110.3 (5.0)	25.2 (5.0)	18.9 (0.8)
Low mulch cover	1	7.5 (2.2)	21.2 (4.1)	30	4.7 (2.7)	25.3 (2.7)	7.3 (1.8)
	2	17.6 (1.0)	1.6 (0.1)	25	18.0 (0.8)	7.2 (0.8)	9.1 (1.4)
	3	24.1 (0.8)	1.1 (0.1)	25	19.0 (1.3)	6.2 (1.3)	6.0 (1.2)
	4	25.5 (0.7)	1.1 (0.1)	28	21.3 (2.2)	6.3 (2.2)	8.0 (1.6)
	5	25.2 (1.2)	1.7 (0.2)	28	22.7 (1.9)	4.9 (1.9)	7.8 (1.8)
			Total	136	85.6 (8.4)	49.9 (8.4)	38.2 (7.8)
High mulch cover	1	1.4 (1.1)	28.8 (1.7)	30	0.4 (0.3)	29.6 (0.3)	10.9 (1.4)
	2	12.9 (1.3)	2.1 (0.1)	25	12.2 (1.7)	13.0 (1.7)	15.2 (1.4)
	3	20.1 (1.3)	1.6 (0.1)	25	14.9 (0.9)	10.3 (0.9)	10.1 (0.6)
	4	20.5 (1.2)	1.5 (0.0)	28	16.3 (0.9)	11.3 (0.9)	13.8 (0.8)
	5	21.6 (1.5)	2.4 (0.1)	28	16.8 (0.9)	10.8 (0.9)	13.0 (0.8)
			Total	136	60.6 (4.5)	74.9 (4.5)	63.0 (5.0)

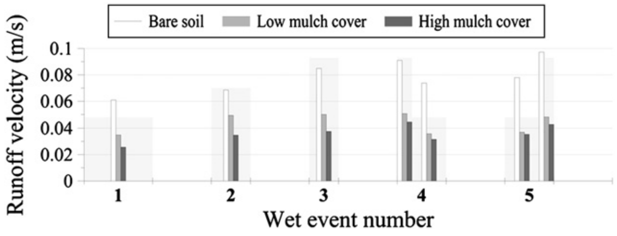

Fig. 6. Average runoff velocities measured during experiments (not subjected to any corrections), for all the soil cover treatments. For the non-uniform patterns (rainfall events 4 and 5) velocity measurements were made for the two rainfall intensities.

motors (Fig. 1 — top). The spatial distribution of the rainfall intensity at the flume level for the three defined positions is shown in Fig. 2 and characteristics were summarized in Table 2.

2.3. Intermittent rainfall experimental procedure

A sequence of five multiple-step intermittent rainfall events was used to simulate rainfall conditions for the study (Fig. 3). The adopted mean rainfall intensities are frequent in many parts of the world; however, the natural intra-event variability was not attempted in this study. A fixed 30 min dry spell interval was always assumed between two consecutive rainfall events, allowing runoff recession to occur, as well as soil drainage. For enhanced evaporation during no-rain periods a set of infrared bulbs with a combined power of 600 W was placed above the soil flume (Fig. 1 — bottom).

The first event was uniform, with intensity equal to 57 mm/h and duration of 35 min. The following event, starting 30 min after the end of the previous event, had duration of 20 min and uniform 84 mm/h intensity, while the third event was also uniform with 112 mm/h rainfall rate during a period of 15 min. Then, two step variable patterns were adopted: one with an advanced pattern and the last one with a delayed pattern, both with a duration of 25 min. These non-uniform events were symmetrical, and combined the lowest and the highest intensities simulated. Although presenting different rainfall intensities and durations, all the five rainfall events delivered approximately the same amount of rainfall. Table 3 shows the characteristics of both rainfall events and dry spells and their sequence in the intermittent rainfall experimental procedure.

Three repetitions of the intermittent rainfall experimental procedure were conducted for each of the three soil cover treatments (bare soil, low mulch cover and high mulch cover).

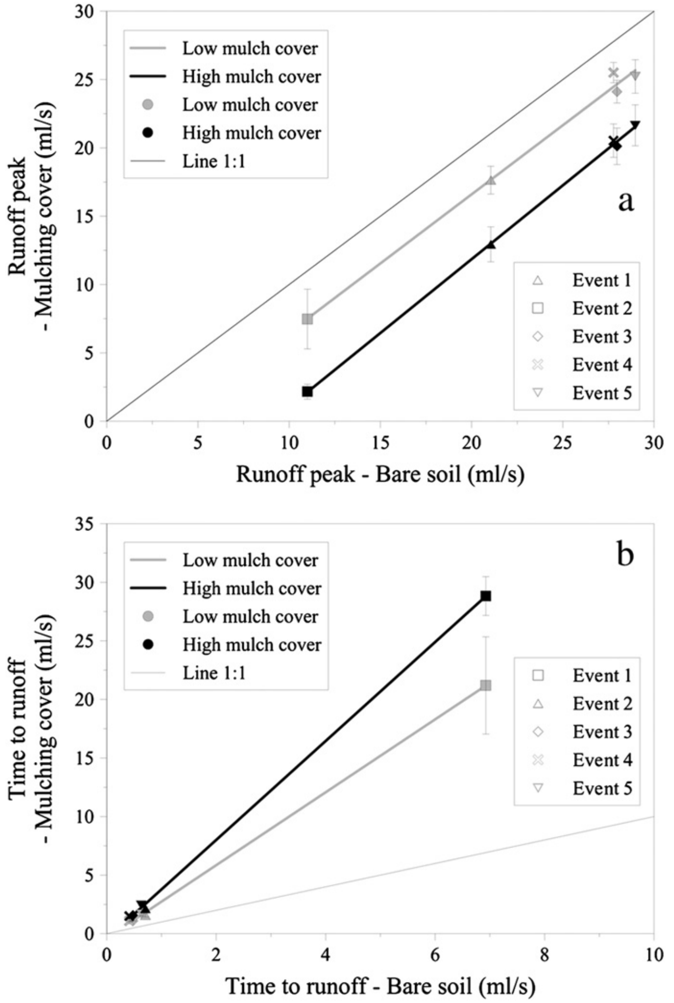

Fig. 8. Relationship between: a) peak discharge for bare soil and mulching treatments; and (b) time to runoff for bare soil and mulching treatments. Average and standard deviation bars of the three repetitions.

2.4. Mulching and soil cover index

Three soil cover treatments were considered: 1) bare soil, without mulch cover; 2) low mulch cover, 2 t/ha density; and 3) high mulch

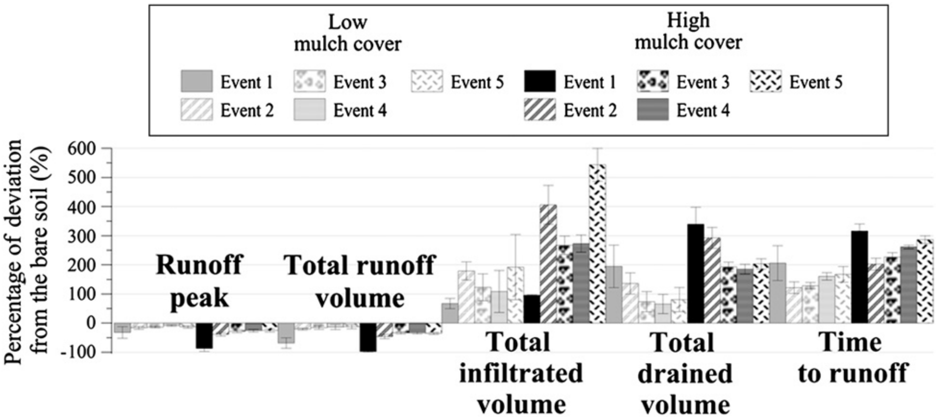

Fig. 7. Results related to the measured flows for the mulching treatments in terms of the percentage of deviation from the bare soil treatment. Average and standard deviation bars of the three repetitions.

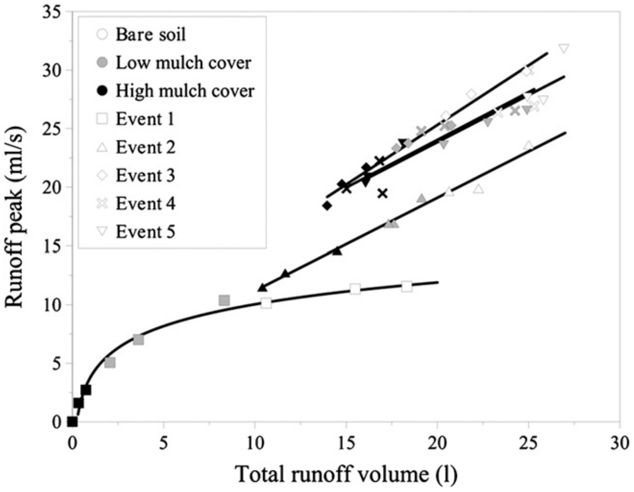

Fig. 9. Comparison between total runoff volume and peak discharge. Curves are only indicative of trends.

cover, 4 t/ha density. Mulch consisted of air dried rice straw (*Oryza sativa* L. ssp. *japonica*). The rice straw cover was monitored by taking digital images of 0.30 m × 0.30 m at the downstream end, middle, and upstream end of the flume surface, to obtain an average soil coverage index along the soil flume surface. The cover index was estimated by using Spring digital imaging processing system (SPRING-DPI/INPE, Camara et al., 1996), as detailed in Fig. 4. The mean values of cover indexes were 63.1 ± 12.3% and 80.3 ± 7.5% for densities of 2 t/ha and 4 t/ha, respectively.

The maximum water retention capacity of the rice straw was evaluated by weighing the rice straw before and after saturation using simulated rainfall. Maximum water retention capacity of the rice straw was 3.4 ± 0.3 L/kg of dry matter. This value was, in accord with the values presented by Findeling et al. (2003), between 3.2 and 3.8 L/kg for different types of mulch.

2.5. Measurements during dry and wet runs

Runoff hydrographs were monitored at the downstream end of the flume by successive sampling of runoff volumes at regular intervals of 15 s. Drainage that occurred along the flume (free drainage installation) was also collected at the bottom end. Collected volumes of runoff were dried at 60 °C for more than one day, to determine sediment concentrations for each run. In addition, the average surface flow velocity was estimated throughout the rainfall events, measuring the time since the addition of a dye tracer at the top of the flume to its visualization at the downstream end.

Soil moisture and soil temperature were recorded throughout the runs at the geometric center of the soil layer (i.e., geometric center of the flume surface at 5 cm depth), using a TDR sensor and a digital thermometer.

3. Results and discussion

3.1. Measured flows and runoff velocities

Fig. 5 presents major fluxes involved in the laboratory experiments: rainfall, runoff, infiltration and drainage. Some of the information obtained from the flow graphics in these figures are summarized in Table 4. Measured runoff velocities are shown in Fig. 6.

In Fig. 7, results for the mulching treatments are presented in terms of the percentage of deviation from the bare soil control. Mulch covers of 2 t/ha and 4 t/ha produced reductions, respectively, of 21% and 51%, in the runoff peak. Such effect was more evident for the first rainfall event, when initial soil water content was low, with reductions of 35% and 87%, respectively. These reductions are due to: 1) protection of the soil from direct impact of drops; 2) higher hydraulic roughness due to the straw cover, retarding surface flow and enhancing infiltration; and 3) water retention of the mulch cover.

Reduction of runoff velocity (Fig. 6) affected significantly the time to runoff at the downstream end of the flume. The runoff start time was significantly higher when mulching was adopted as a treatment, especially for the first rainfall event in the sequence. The mean runoff start time was 4.1 min for bare soil treatment, increasing to 16.7 min

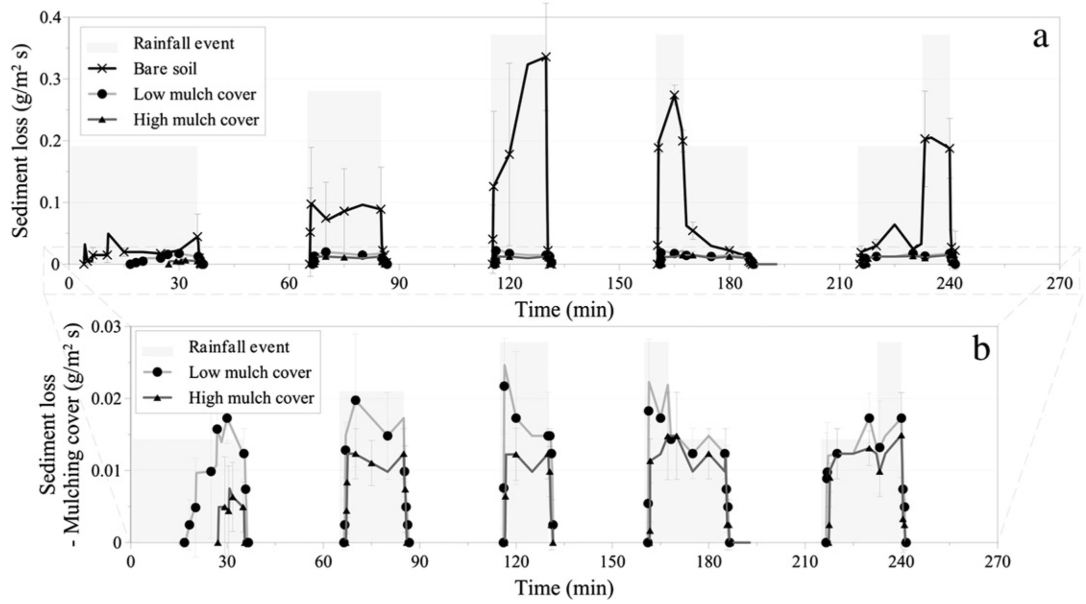

Fig. 10. Erosion rates: a) for the three soil cover treatments; and b) details for the two mulching treatments. Average and standard deviation bars of the three repetitions.

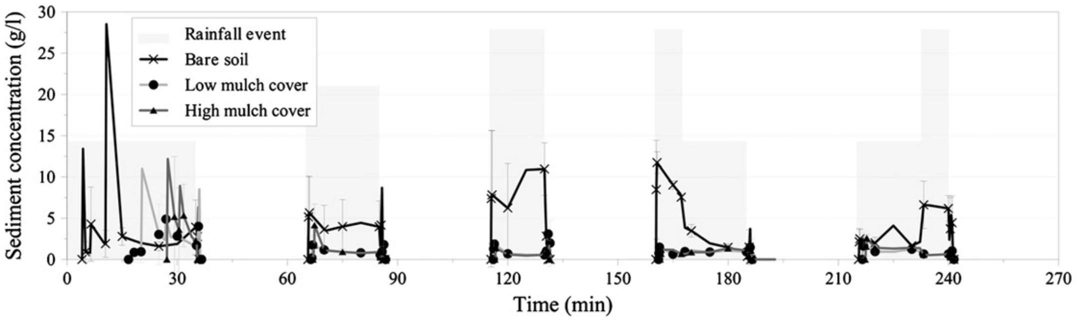

Fig. 11. Sediment concentrations for bare soil and mulching treatments. Average and standard deviation bars of the three repetitions.

and to 27.2 min, for low cover and high cover, respectively. For one out of the three repetitions, using the high mulch cover treatment, no runoff was observed at the downstream end of the flume. Due to the reduced dimensions of the soil surface, runoff stopped shortly after the end of the rainfall events, although percolation persisted longer, with similar durations for all treatments.

Infiltration and abstraction (e.g., surface interception and retention in the straw) were significantly higher for all rainfall events when mulching treatments were used; as a direct consequence, runoff was strongly reduced. For the last two symmetrical rainfall events, differences in infiltration between the mulching treatments were lower than for the first three rainfall events. The advanced peak rainfall event produced very high infiltration plus abstraction in the beginning, which reduced along the event. On the other hand, for the delayed rainfall event, an increase in infiltration was observed when rainfall intensity suddenly increased during the event. Although delayed and advanced peak rainfall profiles produced approximately symmetrical runoff distributions, infiltration plus abstraction rates were significantly different.

Drainage tended to be much lower for the bare soil treatment; higher mulching produced higher drainage volumes (Fig. 5c and Table 4). Increasing mulch cover density also allowed higher interception to occur, which tended to enhance soil protection.

A relevant aspect to be examined is the mulching impact on peak discharge and time-to-runoff at the downstream end of the flume. For these two parameters an approximately linear relationship was found for both mulch densities, with the determination coefficient higher than 0.90 for peak discharge and close to 0.8 for time-to-runoff (Fig. 8). The peak discharge presented angular coefficients close to 1, for both mulch covers (Fig. 8a), for the 15 available situations. Such a result indicates that peak discharge reduction due to mulching could be assumed independent of peak discharge magnitude. On the contrary, the time-to-runoff increase due to mulching was dependent on the time-to-runoff magnitude, as can be seen by the angular coefficients of approximately 3 and 4, respectively, for low and high mulch covers (Fig. 8b).

Table 5
Erosion parameters for all soil cover treatments and rainfall events. Average values and standard deviation (between brackets) for the three repetitions.

Soil cover treatment	Rainfall event	Sediment loss peak (g/m^2 s)	Maximum sediment concentration (g/l)	Total sediment loss mass (g)
Bare soil	1	0.069 (0.030)	43.6 (28.5)	38.6 (9.1)
	2	0.093 (0.080)	10.4 (1.0)	92.6 (76.9)
	3	0.338 (0.030)	14.2 (3.4)	194.7 (72.4)
	4	0.247 (0.014)	11.8 (1.3)	120.0 (10.3)
	5	0.207 (0.066)	9.4 (3.6)	117.0 (29.4)
			Total	562.9 (138.5)
Low mulch cover	1	0.016 (0.003)	18.6 (10.0)	11.3 (4.3)
	2	0.020 (0.005)	2.9 (1.9)	17.2 (5.7)
	3	0.022 (0.003)	4.0 (1.8)	13.7 (5.1)
	4	0.022 (0.003)	2.2 (0.5)	20.1 (2.2)
	5	0.020 (0.000)	2.3 (1.1)	18.3 (1.4)
			Total	80.6 (14.4)
High mulch cover	1	0.007 (0.006)	26.6 (9.9)	2.4 (2.1)
	2	0.011 (0.003)	4.3 (2.4)	11.1 (3.0)
	3	0.011 (0.003)	1.8 (0.8)	8.6 (2.3)
	4	0.013 (0.005)	1.9 (1.0)	15.6 (4.8)
	5	0.015 (0.003)	2.6 (0.4)	15.5 (0.5)
			Total	53.2 (7.8)

Fig. 9 presents an analysis of the ratio between the peak discharge and the total runoff volume. A clear distinction was observed among the different rainfall events and for distinct mulching treatments. The behavior of the first rainfall event was distinct because of the dry initial soil moisture conditions. This affected the erosion process.

3.2. Sediment loss

Erosion rates and sediment loss concentration for all soil cover conditions are presented, respectively, in Figs. 10 and 11. Table 5 summarizes the information related to sediment dynamic. Sediment loss peak, total sediment loss and maximum sediment concentration for the mulching treatments are also presented in Fig. 12, in terms of the percentage of deviation from the bare soil treatment.

Mulching dramatically reduced erosion rates for all rainfall events. More pronounced differences in the sediment loss between two mulch covers were observed for the uniform rainfall profiles, while for time varying rainfall patterns both low mulch and high mulch covers produced similar results. Nevertheless, the advanced rainfall profile produced slightly higher erosion rates when compared to the delayed profile, for both bare soil and low mulch cover treatments. The apparently contradictory behavior of higher soil losses for the advanced rainfall pattern when compared to the delayed pattern could be explained by the sequence of rainfall events, differences in initial soil moisture conditions and by the fact that almost all soil fines (clay and silt) had been washed away from the soil top layer by the three or four previous rainfall events.

The highest sediment concentration peaks occurred during the first rainfall event for all soil cover treatments, when the available soil finest particles were washed away (Fig. 11 and Table 5).

Fig. 13 shows the relationship between runoff peak and sediment loss peak for all soil cover treatments and rainfall events. It is worth noting that a strong increase was observed for the erosion rate in bare soil treatment, while erosion rate tended to remain the same for the mulching treatments.

3.3. Soil moisture and temperature dynamics

Soil moisture and temperature dynamics for both bare soil and mulching treatments are shown in Fig. 14.

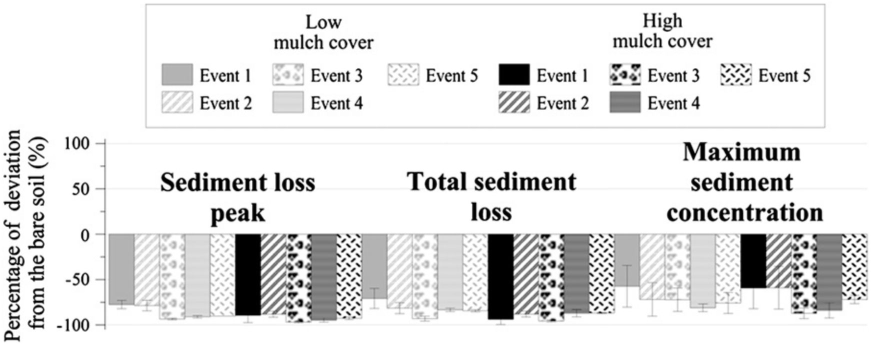

Fig. 12. Percentage of deviation from the bare soil treatment. Average and standard deviation bars of the three repetitions.

Mulching had a significant impact on soil moisture not only during rainfall events but also during dry spells, when infrared bulbs were used. Fig. 15 exhibits the cumulative frequency distribution for moisture; it is clear that the significant persistence of high moisture content occurred when mulch was applied. Such a result is of high interest for soil and water conservation when agricultural cropping is considered. During dry spells for bare soil, a clear reduction in soil moisture was observed. This behavior is partially related to the temperature variations at the top layer of soil. As the rain water was colder than soil, rainfall applications reduced soil temperature during the rainfall events, with similar soil temperatures being observed at the end of each rainfall event for low mulch cover and bare soil treatments.

The lowest soil temperature was observed by the end of the first rainfall event for all treatments, with the most significant decrease occurring for the high mulch cover treatment due to the greater infiltrated volume. It can be shown that mulching promoted a buffer zone reducing the effect of the infrared bulbs, dampening the soil moisture fluctuation all over each intermittent rainfall experimental procedure. Moreover, mulching reduced raindrop impacts on soil physical properties, protecting soil surface from compaction, allowing a higher infiltration rate, and also higher soil moisture (hence, lower soil temperature). Fig. 16 shows the temperature variation during rainfall events and dry spells. Soil heating due to the infrared bulbs in the dry spells was smaller for high mulch as a result of the straw buffering; mulch cover density of 4 t/ha controlled temperature better than the other soil cover treatments.

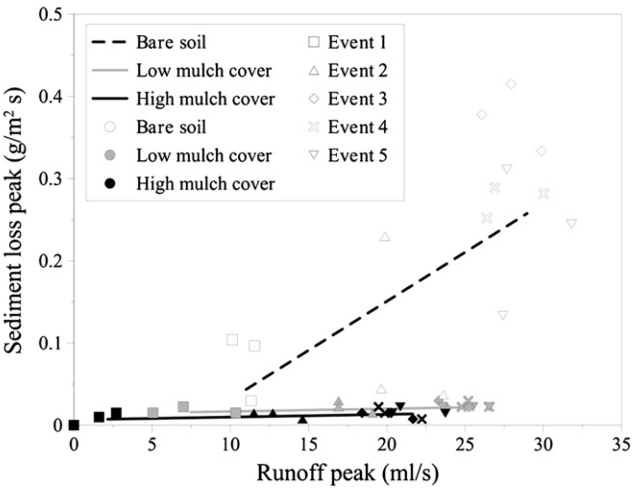

Fig. 13. Relationship between runoff peak and sediment loss peak for all soil cover treatments and for all rainfall events.

The cumulative frequency distribution for temperature is shown is Fig. 17. For high mulch cover treatment, temperature is significantly lower than for the other two treatments.

4. Conclusions

The laboratory experiments described in this paper clearly show that mulch strongly affects infiltration, soil moisture, runoff and erosion. Intermittency and characteristics of sequential rainfall events also influence these processes. More specifically, the laboratory results obtained in this study show that:

1. Mulching reduces peak discharge and runoff values. For example, mulch covers of 2 t/ha and 4 t/ha produce reductions of the runoff peak of 21% and 51%, respectively. Also, mulching increases the time to runoff.
2. Mulching increases infiltration and drainage. High mulch cover treatment results in a significant increase in soil moisture.
3. Mulching reduces dramatically erosion rates for all rainfall events.
4. Mulching controls temperature fluctuations in soil. The effect of mulch on soil temperature shows that the mulch density of 4 t/ha controls the temperature better than the bare soil, where temperature gradients are the highest.

The reduction of sediment transport and increase of infiltration make mulching a strong technique for soil and water conservation. Future research should include field work using different soil mulch covers, in different climatic regions, since the usefulness of mulching is strongly dependent on the rainfall distribution and characteristics over the year.

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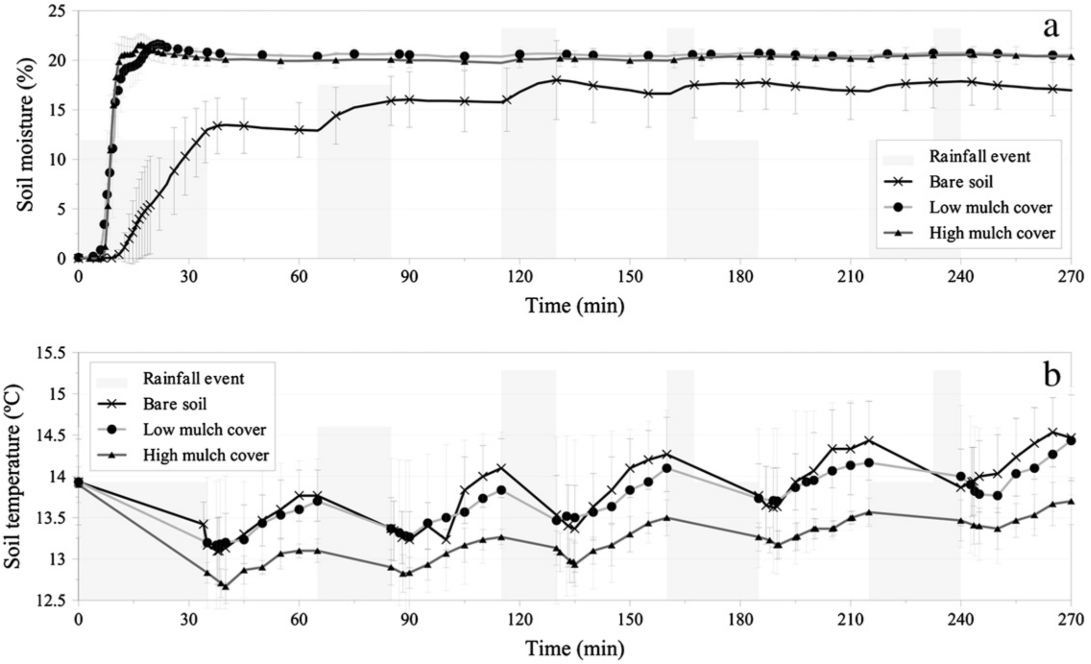

Fig. 14. a) Soil moisture at 5 cm depth (middle of the soil flume) for bare soil and mulching treatments; and b) temperature at 5 cm depth for all soil cover treatments. Average and standard deviation bars correspond to the three repetitions.

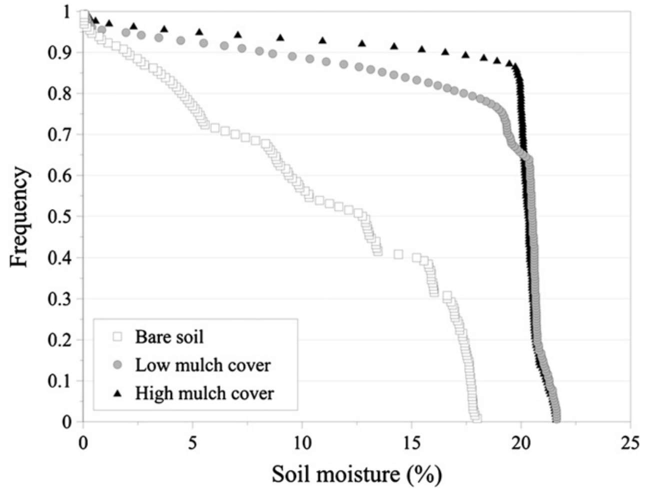

Fig. 15. Cumulative frequency distribution of soil moisture measured for the three soil cover treatments.

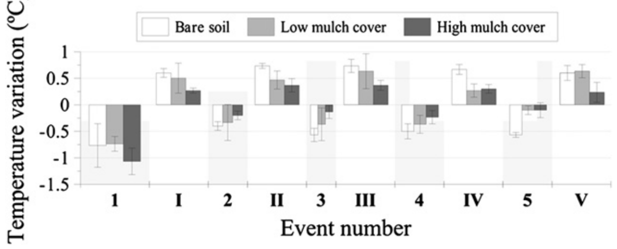

Fig. 16. Temperature variations for both rainfall events and dry spells. Average and standard deviation bars for the three repetitions.

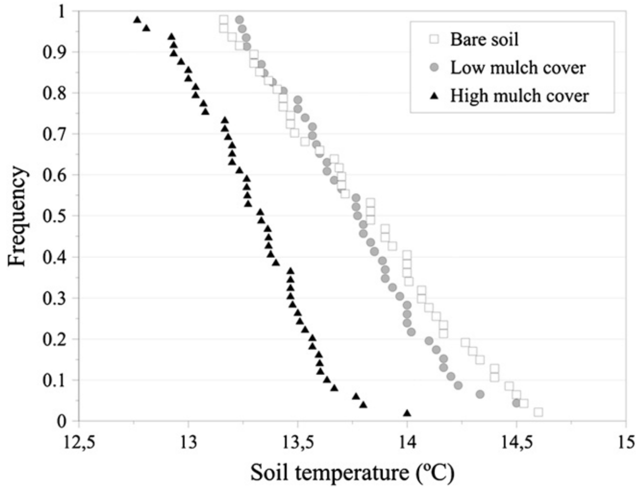

Fig. 17. Cumulative frequency distribution of soil temperature for the three soil cover treatments.

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