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Original Research Article

Duration and intensity of rainfall events with the same erosivity change sediment yield and runoff rates

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ABSTRACT

The effect of different rainfall patterns on surface runoff, infiltration and thus soil losses and sediment concentrations are still in the focus of current research. In most simulated rainfall experiments, precipitation is applied at a fixed intensity for a fixed time. However, the impact of rainfall patterns on soil erosion processes may be different varying the rainfall duration and intensity that produces an event with similar rainfall erosivity values. Twenty-five rainfall events were applied on micro-scale runoff plots in a soil covered with corn straw to evaluate the sediment yield and runoff rates. The different rainfall types were composed by association of duration (Dur) and intensity (IP) with the same erosivity value. The Dur varied from 38 to 106 min and the IP varied from 75.0 to 44.6 mm h^{-1}. The sediment yield varied from 1.89 $\pm$ 1.26 g m^{-2} to 4.02 $\pm$ 2.66 g m^{-2} and runoff ranged from 16.9 $\pm$ 8.74 mm to 32.63 $\pm$ 10.67 mm with highest rates occurring with high intensity and low duration. The highest rainfall intensity provides the maximum sediment yield (0.138 g m^{-2} min^{-1}) and runoff rates (0.87 mm min^{-1}). The time to start surface runoff varied from 14 to 19.2 min and it was longer in treatments with longer durations and low precipitation intensity. No difference was found in the amount of sediments applying rain with the same erosivity and different associations of duration and intensity. However, the intensity and duration of the rain, with the same erosivity, altered the amount and time of runoff. In rainfall experiments with constant intensity and fixed time, the erosion rates depend on the duration of the applied rain. Therefore, the results of this study can contribute to the development of new perspectives in the design of water erosion experiments with simulated rain considering the duration, intensity and also the association of these variables to produce rainfall that delivery the same soil erosion capacity.

1. Introduction

Soil erosion is a complex natural process and it depends of several factors (Alavinia et al., 2018). Therefore, understanding how the erosive process occurs is essential to reduce soil losses to tolerable values using conservation strategies and practices (Angulo-Martínez & Barros, 2015; Cantalice et al., 2017).

In these effort, more than 100 papers per year about soil erosion have been published where artificial rainfall has been applied to inclined plane soil surfaces in laboratory and field experiments, in the past 5 years. In these experiments the rainfall intensities used ranged from less than 50 mm h^{-1} to about 150 mm h^{-1} with events having durations varying from less than 15 min to a few hours (Kinnell, 2020).

In general, erosion occurs due to the combination of two distinct processes: the detachment of soil particles caused by the action of raindrops and subsequently occurring surface runoff or laminar flow, which transports disaggregated soil particles (Alavinia et al., 2018; Cantalice et al., 2017). As a concept, in rainfall-induced

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erosion, the energy of surface runoff is not sufficient to initiate movement of soil particles and only pre-detached soil particles can be transported by shallow surface runoff. Generally, on planar surfaces, the sheet erosion occurs, at the beginning of a rainstorm with rilling only occurring if flow conditions became severe enough cause detachment later (Kinnell, 2020).

Besides that, soil erosion depends on different factors such as rainfall characteristics, infiltration and surface runoff rates, soil properties, and surface features, such as length and steepness of the slope (Alavinia et al., 2018; Arjmand Sajjadi & Mahmoodabadi, 2015; Bagarello et al., 2013). Among rainfall characteristics the intensity, the duration and kinetic energy are main factors affecting rainfall-induced erosion processes and/or that determine the erosive potential or erosivity (Angulo-Martínez & Barros, 2015; Katebikord et al., 2017).

Rainfall intensity is fundamental to control runoff and erosion. Its effect on runoff can be understood through its influence on infiltration, although it is not straightforward. Increasing rainfall intensity may lead to increased infiltration because of spatial heterogeneity in infiltration characteristics of the soil surface and the development of such crusts (Alavinia et al., 2018; Parsons & Stone, 2006). On the other hand, infiltration is reduced by the formation of soil crusts (Almeida et al., 2018).

Flanagan et al. (1987) compared the effects of six different rainfall patterns on runoff and soil loss and reported that the pattern with maximum intensity near the end of the rainstorm was associated with the highest values of runoff and soil loss. It is kinetic energy that controls surface sealing, soil water infiltration and consequently runoff and the detachment of particles, and thus soil loss. So, the effects of different heavy rainfall events with the same averages intensity on the soil surface may be different because there is no linear relationship between rainfall intensity and its kinetic energy (Parsons & Stone, 2006). Dunkerley (2012) undertook a series of field experiments in which rainstorms had different rainfall patterns and found that rainfall pattern affected the infiltration and runoff. Alavinia et al. (2018) evaluated four simulated rainfall patterns with the same total kinetic energy and found significant differences in soil losses among the different rainfall patterns and stages. For varying-intensity rainfall patterns, the dominant sediment transport mechanism was not only influenced by raindrop detachment but also was affected by raindrop-induced shallow flow transport. He et al. (2017) observed low rainfall intensity boosted but the high rainfall intensity lowered the clay fraction comparing rill erosion under continuous and intermittent rainfalls by using laboratory experiments.

Kinetic energy per unit area during a given rainfall event and peak intensity are commonly used parameters to state erosivity. At the same time, erosivity is not only a function of intensity and duration, but also of rainfall characteristics such as raindrop speed and diameter. These parameters can be set constant using rainfall simulators (Iserloh et al., 2012; Seitz et al., 2015).

Simulators have been used by several researchers in the evaluation of soil erosion and soil water infiltration in the laboratory (Gan et al., 2020; Goebes et al., 2014; Kavian et al., 2018; Lassu et al., 2015), nutrient losses (Gan et al., 2021; Wu et al., 2021), carbon loss (Wang et al., 2021), soil erosion in the field (Alves Sobrinho et al., 2008; Wang et al., 2017; Almeida et al., 2018; Moraes et al., 2019; Seitz et al., 2019; Falcão et al., 2020; Procházková et al., 2020) and soil water infiltration in the field (Almeida et al., 2018). Falcão et al. (2020) evaluated the impacts of intense modification of land use and land cover on surface runoff and soil erosion using three constant rainfall intensities (60, 90, and 120 mm h^{-1}) for 1 h and found that natural regeneration processes tend to improve the soil ecosystem services, improving infiltration and reducing surface runoff and soil erosion. Procházková et al. (2020) evaluated the impact of the conservation tillage on reducing the soil loss due to erosion under simulated rainfall and the authors observed a positive soil conservation effect. Under simulated rainfall, Seitz et al. (2020) investigating how biochar particles instantly change erodibility by rain splash and the initial movement of soil water in a small-scale experiment and found evidence that biochar amendments reduce soil degradation by water erosion. Simulators also have been used by Marston et al. (2020) to separate the impact of anthropic erosion from changes that would have occurred without human interference (geological or natural erosion).

Despite the several advantages of rainfall simulators, in experiments with applied rainfall, there are some limitations, generally described in the characterization of the simulators prototype. In the case of the present study, the simulator developed by Alves Sobrinho et al. (2008) can show under- or overestimation of soil losses and runoff rates in small plots and does not induce rilling processes, as required in studies of pesticide transport or transport of elimination of mulch. The portable rainfall simulators generally use experimental plots with an area of less than 5.0 m^2, most of them smaller than 1.0 m^2 (Iserloh et al., 2013). These small-plot simulators are essential tools for research on surface hydrological processes and the dynamics of soil erosion (Seitz et al., 2019; Wang et al., 2017) and these limitations do not compromise the results produced with the simulators (Iserloh et al, 2012, 2013; Marques et al., 2019).

In many studies the effects of rainfall patterns on soil erosion processes have been investigated and the authors reported that rainfall patterns were associated with the highest values of runoff and soil loss, infiltration, and higher sediment concentrations (Flanagan et al., 1987; Parsons & Stone, 2006; Dunkerley, 2012; An, Zheng, & Han, 2014; Mohamadi & Kavian, 2015; Alavinia et al., 2018). These studies have used patterns with varying intensity, rainstorms with the peak instantaneous intensity at the beginning, at the middle and at the end and storms with increasing rainfall intensity.

On the other hand, in most simulated rainfall experiments, precipitation is applied at a fixed intensity for a fixed time. Total amounts or average rates of soil discharged in experiments of fixed duration will produce results that are dependent on the duration of the experiment. This needs to be considered when designing and analyzing experiments using artificial rainfall to erode soils (Kinnell, 2020).

The impact of rainfall patterns on erosion processes may be different using rainfall characteristics that produce an event with similar rainfall erosivity values. In this study we hypothesize that the sediment yield and runoff rates can be altered by rainfall events with association of different intensity and duration to delivering the same total erosivity. So, the events were normalized by erosivity, and duration and intensity were varied. Therefore, in this study five simulated rainfall patterns were applied on a small-scale plot to investigate soil erosion processes.

2. Material and methods

2.1. Experimental area

The experiment was conducted in the municipality of Seropédica, Rio de Janeiro, Brazil (22° 46 ′S, 43° 41′ W and average altitude of 33 m) in March 2018. The topography is undulated, and the mean slope of the experimental area is 9.0%. The experiment was carried out on arable land after harvesting corn crop (110 days after sowing). Sowing was conducted with 10 seeds per linear meter and spacing of 1.0 m between the rows.

2.2. Characterization of the soil

The *Argissolo Vermelho-Amarelo Distrófico típico* profile (Dystrophic Acrisol with a clay loam texture) of the experimental area was previously described by Carvalho et al. (2009) and some characteristics are presented in Table 1.

The total organic carbon, macroporosity, microporosity and soil bulk density were evaluated in three layers, 0–10 cm, 10–20 cm, and 20–40 cm. All analyses of these attributes were performed following the methodologies described by Teixeira et al. (2017). There was no significative difference of soil attributes between the treatments. The means (considering five replicates for each treatment) values of total organic carbon, macroporosity, microporosity and soil bulk density in the 0–10 cm layer were: 16.06 g kg^{-1}, 14.35%, 28.56%, 1.34 g cm^{-3}, respectively; for 10–20 cm layer the mean values were: 13.58 g kg^{-1}, 6.50%, 29.55% and 1.53 g cm^{-3}, respectively; for 20–40 cm layer the values were: 4.08 g kg^{-1}, 9.56%, 33.09%, 1.54 g cm^{-3}, respectively.

2.3. Evaluation of soil erosion

For the application of rainfall, a rotating disk rain simulator developed by Alves Sobrinho et al. (2008) was used. The simulator operates with two Veejet 80.150 nozzles parallel to each other, installed at a height of 2.3 m above the ground and with a service pressure of 35.6 kPa. The micro-plots have an area of 0.7 m^2 and are delimited by galvanized steel plates, with a funnel at the end, which allows collecting the volume of water drained on the surface (Alves Sobrinho et al., 2008). Although most portable simulators have a plot-area less than 1.0 m^2 (Iserloh et al., 2013), the device used in this study is suitable for generating only interrill erosion (Marques et al., 2019).

Before each rainfall application, the water content in the soil was standardized within the treatments by wetting the plots and to quantify the soil water content prior to rainfall events. Three soil samples for treatment were collected next to each plot at 0–10 cm and 10–20 cm. After the pre-wetting stage, the rainfall application was started and the rainfall duration was pre-established for each treatment, regardless of the time of beginning surface runoff. When the runoff started, volume measurements were made every minute and every 5 min a sample was collected to estimate the sediment yield. In the laboratory, aluminum sulfate (0.018 mol L^{-1}) was added to the samples for flocculation and precipitation of suspended solids. After 24 h, the excess water was removed from each sample and the solid material was dried at 105 °C. After this step, sediment mass was calculated by means of the sum of the samples coming from the same rainfall event.

2.4. Characterization of treatments

The treatments adopted were characterized by a rainfall duration of 60 min and intensity precipitation (IP) of 60 mm h^{-1}, which has been used as reference in studies of soil erosion and water infiltration in different regions of Brazil (Almeida et al, 2016, 2018; Carvalho et al., 2015; Moraes et al., 2019; Santos et al., 2014). From the equipment's operating characteristics (drop height = 2.3 m, mean drop diameter = 2.0 mm, water pressure = 34.0 kPa), the kinetic energy of the reference rainfall (KEs) was calculated and, subsequently, its erosivity, according to the methodology proposed by Wischmeier and Smith (1978). Using the computational routine proposed by Alves Sobrinho et al. (2008), KEs is estimated by the precipitated depth and drop velocity, which depends on the drag coefficient, calculated from its mean diameter. The other IP values were adopted from the reference rain, with a variation of ±7.5 and ± 15.0 mm h^{-1}. Thus, the nominal IPs of 45.0, 52.5, 60.0, 67.5 and 75.0 mm h^{-1} were evaluated, and for each of them, the rainfall durations were defined by the computational routine, maintaining the simulator characteristics and the erosivity value, previously calculated.

After manual calibration of the equipment, the simulated rainfall in the field showed IP of 44.6, 52.9, 60.4, 67.4 and 75.0 mm h^{-1}, which associated with the durations of 106, 78, 60, 48 and 38 min characterized the evaluated treatments. The experimental design was a randomized block design, with five treatments and five replicates each.

2.5. Estimation of the percentage of soil cover

To evaluate soil surface cover by corn straw in each experimental plot, digital photos were taken after each rainfall event. The image acquisition was done at a height of 1.50 m from the soil surface, focusing on the plot area of 0.7 m^2 (Almeida et al., 2016). The soil cover index (SCI) was estimated using the Serobin algorithm (Cruz et al., 2008). For each treatment, a base image was used, in which ten representative points of the plant attribute and ten points of the soil attribute were identified and this image was used to classify and estimate the SCI in the others (Almeida et al., 2016). In the binary images classified to estimate the percentage of soil cover by corn straw, the white color represents the plant and the black color the soil (Fig. 1). This method has proven to reliably detect the contrasts between the corn straw and the soil surface (Almeida et al., 2016; Cruz et al., 2008).

The percentage of soil cover by corn straw varied from 51.69% in the IP 44.6 mm h^{-1} and Dur 106 min treatment to 79.52% in the IP 67.4 mm h^{-1} and 48 min treatment within an overall mean percentage of soil cover equal to 66.67% (Table 2). The percentage of soil cover was lower at IP 44.6 mm h^{-1} and Dur 106 min (51.69%), which corresponds to 35% less compared to the highest percentage in absolute value of 79.52% at IP 67.4 mm h^{-1} and Dur 48 min.

Although the percentage of vegetation cover is different between treatments, the amount of dry matter of corn straw (corn straw biomass) is the same between treatments. Possibly, the amount of stalk and leaves explains this variation in the coverage index, because with more leaves on the surface and, depending on

Table 1
Characteristics of the *Argissolo Vermelho-Amarelo Distrófico* of the experimental area.

Horizon	Depth (cm)	Granulometric composition (%)				
		Sand (2–0.05 mm)	Silt (0.05–0.002 mm)	Clay (<2μ)	Degree of flocculation (%)	Silt/Clay
A	0–16	58	16	26	27	0.58
AB	16–27	50	14	36	19	0.38
BA	27–46	42	14	44	44	0.30
Bt_1	46–90	46	12	42	77	0.30
Bt_2	90–117	40	15	45	82	0.33
Bt_3	117-155+	30	12	58	99	0.21

Source: Modified of Carvalho et al. (2009).

(a) (b)

Fig. 1. Digital image (a) and binary (b) used for the estimation of the vegetation cover index.

Table 2
The percentage of soil cover and corn straw biomass (mean ± standard deviation).

Treatments	Soil cover (%)		Corn straw biomass (kg m^{-2})	
IP 44.6 mm h^{-1} and Dur 106 min	51.69 ± 0.10	b	0.40 ± 0.12	a
IP 52.9 mm h^{-1} and Dur 78 min	69.35 ± 0.11	a	0.45 ± 0.10	a
IP 60.4 mm h^{-1} and Dur 60 min	68.83 ± 0.15	a	0.42 ± 0.02	a
IP 67.4 mm h^{-1} and Dur 48 min	79.52 ± 0.10	a	0.39 ± 0.06	a
IP 75.0 mm h^{-1} and Dur 38 min	63.97 ± 0.07	a	0.50 ± 0.13	a
Overall Mean	66.67 ± 0.10		0.43 ± 0.08	
CV (%)	16.43		22.01	

Means followed by equal letters in the column, for the same variable, do not differ by LSD test ($p < 0.05$).

their disposition, the percentage of soil coverage can be increased, in comparison to situations with a greater amount of stems on the surface.

2.6. Statistical analysis

The statistical analysis was conducted with R version 3.5.1 (R Core Team, 2018). To meet the assumptions of the analysis of variance the residuals were verified by tests of normality and homogeneity. The normality was verified by the Shapiro-Wilk test (Shapiro & Wilk, 1965) and the homogeneity by Bartlett test (Bartlett, 1937). The calculated probability for normality and homogeneity of sediment production were $p = 0.2911$ and $p = 0.5748$, respectively; and for the runoff $p = 0.9083$ and $p = 0.3270$, respectively. No transformation of runoff and the sediment production data was needed. Differences between the treatments levels were verified by analysis of variance (test F, $p < 0.05$) considering the completely randomized blocks with five treatments I) IP 44.6 mm h^{-1} and Dur of 106 min; II) IP 52.9 mm h^{-1} and Dur of 78 min; III) IP 60.4 mm h^{-1} and Dur of 60 min; IV) IP 67.4 mm h^{-1} and Dur of 48 min and V) IP 75.0 mm h^{-1} and Dur of 38 min), with five replications each one. When a significant difference between treatments was found (by the F test), the treatments were compared by LSD test (Least Significant Difference), considering a level of significance of 5%.

3. Results and discussion

3.1. Time to start runoff and accumulated sediment yield and runoff

The time required to start the runoff differed considerably between the applied rainfalls. The highest flow times were verified for the treatments I (IP 44.6 mm h^{-1} and Dur of 106 min), II (IP 52.9 mm h^{-1} and Dur of 78 min), III (IP 60.4 mm h^{-1} and Dur of 60 min), and V (IP 75.0 mm h^{-1} and Dur of 38 min), ranging from 11.6 min at V to 19.2 min at treatment II. The highest standard deviation was also observed in the treatment I. Otherwise, the shortest run-out time was found at treatment IV (IP 67.4 mm h^{-1} and Dur of 48 min), with a mean value of 5.8 min and the lowest standard deviation (Table 3).

This difference might arise from the characteristics of the corn straw on the soil surface and the physical attributes of the soil, since the soil water content prior to the application of rainfall was homogeneous among the treatments. In relation to the straw, the IP 67.4 mm h^{-1} and Dur 48 min treatment (IV) was quantified with less amount and greater percentage of soil cover, in absolute value, due to the lower stem/leaf ratio. The greater amount of fine leaves may have shortened the time for water to transpose the vegetation cover and reach the soil surface faster than in other treatments.

The surface runoff is different between the applied rainfall events. The smallest runoff (16.90 mm) was observed from the rainfall of Treatment V (Table 4). This depth is due to the shorter duration of rain, although it is associated with higher IP and low Dur. The largest and the lowest accumulated depth of superficial runoff were 16.90 mm and 32.63 mm, respectively, at the treatments V and II.

The leaf strip depends on several factors such as precipitated leaf area, surface sealing, water infiltration in the soil, soil erodibility and intensity, of which the combined effect is less clear (An, Zheng, & Han, 2014; Ran et al., 2012; Wang et al., 2017). Kinnell (2020) states that surface runoff is directly related to rainfall intensity, rainfall time and applied depth, although this effect is not fully understood (Wang et al., 2017). Considering the absolute values, in general, in the present study, the leaflet decreased with increasing precipitation intensity. This fact is related to the decrease of the water depth applied in rainfall events of greater intensity, due to the shorter duration of these rainfall.

The sediment yield varied from 1.89 g m^{-2} with IP of 52.9 mm h^{-1}, to 4.02 g m^{-2}, at 44.6 mm h^{-1}, with a mean of 3.08 g m^{-2}. The highest absolute value occurred at IP 44.5 mm h^{-1} and Dur 106 min and the lowest at IP 52.9 mm h^{-1} and Dur 78 min. However, different associations of rainfall duration and intensity did not significantly alter sediment yield. This fact is related to the corn straw on the soil surface which reduces the energy of the rainfall impact and consequently, the soil particle detachment. Other authors have verified the effect of soil cover in reducing the runoff and sediment production under simulated rainfall conditions (Ran et al., 2012; Wang et al., 2017). In initial development of soybean under no-tillage, Almeida et al. (2016) found that the percentage of coverage from corn straw was 37.37% and these corn residues were effective in reducing soil erosion rates. The effect of residues from

Table 3
Time to start runoff and soil water content (mean ± standard deviation) before rainfall application in *Argissolo Vermelho-Amarelo Distrófico típico* under different treatments at the study site.

Treatments	Time to start runoff (min)		Soil water content ($g\ cm^{-3}$)			
			0–10 cm		10–20 cm	
IP 44.6 mm h^{-1} and Dur 106 min	19.2 ± 12.87	b	0.32 ± 0.03	a	0.31 ± 0.03	a
IP 52.9 mm h^{-1} and Dur 78 min	14.0 ± 9.27	ab	0.30 ± 0.03	a	0.32 ± 0.03	a
IP 60.4 mm h^{-1} and Dur 60 min	16.0 ± 7.54	b	0.30 ± 0.03	a	0.30 ± 0.03	a
IP 67.4 mm h^{-1} and Dur 48 min	5.8 ± 3.56	a	0.29 ± 0.03	a	0.32 ± 0.02	a
IP 75.0 mm h^{-1} and Dur 38 min	11.6 ± 6.18	ab	0.31 ± 0.02	a	0.33 ± 0.02	a
Overall mean	13.32		0.30		0.31	
CV (%)	48.22		9.91			

Means followed by equal letters in the column, for the same variable, do not differ by LSD test ($p < 0.05$).

the corn residues in reducing breakdown and soil loss from erosion was also verified by Engel et al. (2009).

In the same experimental area, Carvalho et al. (2015) investigated the water erosion and soil water infiltration in different stages of corn development and tillage systems and quantified, in a bare soil conditions, a mean sediment yield of 9.5 g m^{-2}, applying rainfall events of 60 mm h^{-1} with a duration of 60 min after runoff began, which is almost four times greater than we quantified in the present study in the IP 60.4 mm h^{-1} e Dur 60 min treatment. The differences in sediment production can be explained mainly by the corn straw cover of the soil in this study, associated with the organic carbon content and porosity, which demonstrate the positive contribution of soil cover to reduce land degradation and soil erosion.

Thus, there are several factors that can interfere in the production of sediments, besides the physical characteristics of the rainfall events, roughness, soil cover and soil attributes (Alavinia et al., 2018; Almeida et al., 2016) and the rainfall simulators characteristics (limitations) (Alves Sobrinho et al., 2008; Iserloh et al., 2013). Another reason reported by Iserloh et al. (2013), evaluating portable rainfall simulators in Europe, are the kinetic energy values produced by the simulators. According to the authors, these values are lower when compared to those of natural rainfalls reported in the literature, mostly because of low drop fall heights.

Although the percentage of vegetation cover is different between the rainfall intensities, the amount of corn straw (dry biomass) used does not differ between treatments (showed in Table 2). This is explained by the stem/leaf ratio, since a larger the number of leaves and depending on their arrangement on the surface, less mass per square meter can lead to greater soil cover. The corn residues, despite offering low ground cover, are effective in reducing soil erosion rates, while soybean cultivation has not yet been able to protect the soil from the impact of raindrops like reported by Almeida et al. (2016) and Engel et al. (2009).

Table 4
Surface runoff and accumulated sediment yield (mean ± standard deviation) in *Argissolo Vermelho-Amarelo Distrófico típico* at the study site.

Treatments	Runoff (mm)		Sediment (g m^{-2})	
IP 44.6 mm h^{-1} e Dur 106 min	32.35 ± 20.27	b	4.02 ± 2.66	a
IP 52.9 mm h^{-1} e Dur 78 min	32.63 ± 10.67	b	1.89 ± 1.26	a
IP 60.4 mm h^{-1} e Dur 60 min	23.97 ± 14.21	ab	2.47 ± 1.16	a
IP 67.4 mm h^{-1} e Dur 48 min	29.96 ± 7.88	ab	3.86 ± 1.91	a
IP 75.0 mm h^{-1} e Dur 38 min	16.90 ± 8.41	a	3.17 ± 2.13	a
Overall mean	25.96		3.08	
CV (%)	37.61		59.00	

Means followed by equal letters in the column, for the same variable, do not differ by LSD test ($p < 0.05$).

3.2. Surface runoff and sediment yield rates

Initially, the surface runoff rates are low and with an increase in the duration of rainfall the flow rates increase, reaching higher values at the end of the rainfall events. In general, the highest rates are observed for rainfall with the highest precipitation intensity (Fig. 2a). This fact was also reported by other authors (He et al., 2017; Ran et al., 2012; Wang et al., 2017).

In the treatment with IP 44.6 mm h^{-1} and Dur 106 min, there is a different behavior showing a different pattern in comparison to other treatments. This behavior occurs because of the effects of the roughness of the land surface and physical barriers such as straw on the soil surface (Almeida et al., 2016, 2018), which allows the accumulation of water in small puddles. Over time, the water acquires enough energy to break the physical barriers such as straw on the soil and the microrelief of the land and it flows into the collecting channel, increasing the volume drained at a given moment.

Like the surface runoff, the sediment yield rates for treatments are lower initially, except for IP 67.4 mm h-1 and Dur 48 min (Fig. 2b). As rainfall duration increased, sediment yield rates for all rainfall declined, although not so evidenced for IP 75.0 mm h^{-1} and Dur 48 min, because of the short duration of rainfall. In general, the highest sediment yield and runoff rates were observed for rainfall with the highest rainfall intensity, especially at 75.0 mm h^{-1} and Dur 38 min and IP 67.4 mm h^{-1} and Dur 48 min. In these treatments, the maximum sediment yield rate was 0.138 g m^{-2} min^{-1} and 0.113 g m^{-2} min^{-1}, respectively. For runoff rates, the maximum values were 0.75 mm min^{-1} and 0.87 mm min^{-1}. In the same experimental area, Carvalho et al. (2012) obtained maximum soil loss and runoff rates of 0.165 g m^{-2} min^{-1} and 0.138 mm min^{-1}, respectively, after 24 min from the beginning of the application of a simulated rainfall of

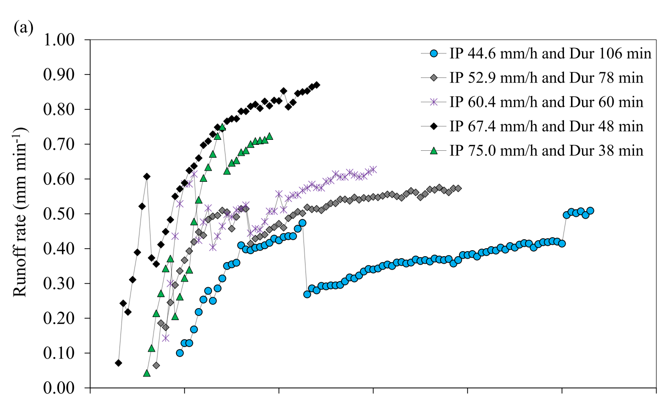

Fig. 2. Runoff rate (mm min^{-1}) (a) and sediment yield rate (g m^{-2} min^{-1}) (b) for the types of simulated rainfall in *Argissolo Vermelho-Amarelo Distrófico típico*.

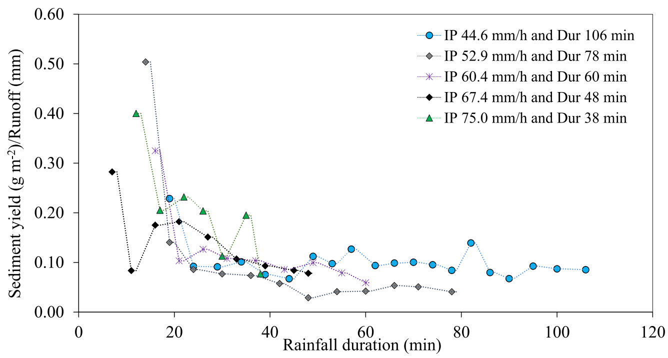

Fig. 3. Sediment production and surface runoff as a function of rainfall duration for the different treatments in *Argissolo Vermelho-Amarelo Distrófico típico*.

30 mm h^{-1}. The results were obtained on a bare soil, however under corn straw cover there was no surface runoff.

The difference between the sediment production rates is related to the corn straw covering the soil surface which reduces the raindrops impacts and consequently the soil particles detachment comparing to the bare soil, the characteristics of rainfall simulators and the size of plots. Besides that, the physical effect of the corn roots favors soil porosity, structuring the soil and, creating spaces for water infiltration, which reduces soil erosion (Carvalho et al., 2015). In addition, the sediment production rate or total amounts of soil discharged are dependent of rainfall intensity and duration in many experiments with fixed duration intensity (Kinnell, 2020). In the present study, this direct relationship was not observed because we varied the duration and intensity and other factors, such as soil cover, water infiltration.

The relationship between sediment production and surface runoff by the different rainfall associations is initially high, especially in treatments with higher intensities and shorter durations, when runoff is lower. As rainfall duration increases, runoff increases because rainwater input is constant. Consequently, the ratio between sediment production and runoff decreases (Fig. 3).

From 15 min after runoff, the sediment/runoff ratio decreases markedly. The sediment/runoff ratio in IP 44.6 mm h^{-1} and Dur 106 min treatment surpasses the others after 45 min of rainfall, with a maximum value of 0.15 g m^{-2} mm^{-1}. After that time, the medium sediment/runoff ratio value was 0.093 g m^{-2} mm^{-1}. These results can explain by variation of sediment yield and runoff showed in Fig. 2. In addition, under higher rainfall and higher intensities there may also be increased sediment production rates, and some studies (Alavinia et al., 2018; He et al., 2017; Kinnell, 2020) have reported a linear relationship between surface runoff depth and sediment production.

4. Conclusions

In this study, we investigate the hypothesis that rainfall with equal erosivity and association of different duration and intensity alter the erosion process differently. We quantify the effect of five rainfall events with the same erosivity and different association of rain duration and intensity, on surface runoff and sediment yield, on a soil covered with corn straw.

Our findings indicate that rainfall with equal erosivity and distinct duration and intensity influence the runoff and the time to start runoff, but it does not alter the sediment production. Higher precipitation intensities produce higher runoff rates and higher sediment detachment rates. The sediment production/runoff relationship is initially high especially in the treatments with higher intensities and shorter durations. As rainfall duration increases, runoff increases and consequently, the sediment production/runoff relationship decreases. The time to start surface runoff is longer in treatments with longer durations and low precipitation intensity.

Therefore, the results of this study can contribute to the development of new perspectives in the design of erosion experiments with simulated rainfall. This is particularly true considering the duration, intensity and the association of these variables to produce rainfall that delivery the same capacity to erode the soil and consequently leads to a better understanding of the erosion process.

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