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Water erosion in surface soil conditions: runoff velocity, concentration and D_{50} index of sediments in runoff

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ABSTRACT: Water erosion and contamination of water resources are influenced by concentration and diameter of sediments in runoff. This study aimed to quantify runoff velocity and concentration and the D_{50} index of sediments in runoff under different soil surface managements, in the following treatments: i) cropped systems: no-tilled soil covered by ryegrass (*Lolium multiflorum Lam.*) residue, with high soil cover and minimal roughness (HCR); no tilled soil covered by vetch (*Vicia sativa L.*) residue, with high soil cover and minimal roughness (HCV); chiseled soil after ryegrass crop removing the above-ground residues and keeping only the root system, with high roughness (HRR); chiseled soil after vetch crop removing the above-ground residues and keeping only the root system, with high roughness (HRV); ii) bare and chiseled soil, with high roughness (BHR). The research was conducted on a Humic Dystrupept under simulated rainfall. The design was completely randomized and each treatment was replicated twice. Eight rainfall events of controlled intensity (65 mm h^{-1}) were applied to each treatment for 90 minutes. The D_{50} index, runoff velocity and sediment concentration were influenced by crop and soil management. Runoff velocity was more intensely reduced by cover crop residues than by surface roughness. Regardless of surface condition, the D_{50} index and concentration of sediment in runoff were lower under ryegrass than vetch crop. Runoff velocity and the D_{50} index were exponentially and inversely correlated with soil cover by residues and with surface roughness, while the D_{50} index was positively and exponentially correlated with runoff velocity.

Keywords: hydric, erosion, soil management, conservation tillage

Introduction

Understanding the effect of water flow velocity, concentration and diameter of sediments in runoff is necessary to predict water erosion, mainly, the runoff capacity to transport chemicals that can contaminate water resources (Kuhn et al., 2012). Soil surface characteristics with greater influence on water erosion, related to runoff velocity and concentration and diameter of eroded sediments, are soil cover by crop residues and soil surface roughness (Cogo et al., 1984; Engel et al., 2009). These characteristics are usually found in conservative soil tillage (Bertol et al., 2003), represented by no-till and minimum tillage.

Crop residues can dissipate kinetic energy from raindrops and, in part, from runoff by slowing it down, hence, preventing soil disaggregation and sediment transport (Engel et al., 2009). Moreover, residues filter runoff, retaining coarse sediments and reducing sediment load. Roughness increases surface tortuosity and, therefore, decreases runoff velocity and its ability to detach the soil and transport sediments (Rodríguez-Caballero et al., 2012), however, this effect is ephemeral.

Grasses can be more efficient than leguminous crops to control water erosion. Grass biomass is usually composed of long and narrow leaves and stems and, for the same mass, it presents more efficient and persistent soil cover than broad-leaf plants do (Gilmour et al., 1998). In addition, grass roots can improve soil aggregate stability and increase soil resistance to water erosion (Martinez-Trinidad et al., 2012).

Off-site erosion damage, especially related to surface water contamination, depends on the quantity and size of eroded sediments as well as their adsorption capacity of chemical species (Kuhn et al., 2012). Therefore, the higher the concentration of fine-size sediments in the flow, the higher the risk of environmental contamination (Barbosa et al., 2010; Kuhn et al., 2012).

This study aimed to quantify and correlate runoff velocity, sediment concentration and the D_{50} index of sediments in runoff under different soil surface conditions. Therefore, a simulated rainfall study was performed in plots with soil covered by crop residues of ryegrass or vetch, soil chiseled after ryegrass or vetch crops where the above-ground residues were removed and, also, a bare and chiseled soil.

Materials and Methods

Description of the study site

The research was conducted in an experimental field with a mean slope of 0.134 m m^{-1} (moderately sloping surface), located in southern Brazil at coordinates 27°47′ S and 50°18′ W. The climate is Cfb type according to the Köppen classification with average annual rainfall of 1,535 mm (Schick et al., 2014). The altitude of the experimental site is 908 m and the soil is Humic Dystrupept.

Prior to this experiment, the study site was submitted to simulated rainfall with soybean (*Glycine max L.*) and maize (*Zea mays L.*) crops sown in contour and downhill in no tillage, except for the site where the bare soil treatment was installed, which was already uncropped. At the end of the last crop cycle, above-ground residues were removed and then ryegrass (*Lolium multiflorum Lam.*) and vetch (*Vicia sativa L.*) were broadcast sown and seeds were incorporated into the soil with light disking in the transverse direction of the slope. Ryegrass was sown at 40 kg ha^{-1}, whereas vetch was sown at 60 kg ha^{-1}.

The experimental plots were 11-m long in slope direction and 3.5-m wide. The lateral and upper plot boundaries were delimited by galvanized sheets with 0.2 m of height and were inserted 0.1 m into the soil. At the lower boundary, a runoff collector was installed, connected to a plastic tube with 75-mm diameter and 6-m long. The tube canalized runoff flow to a trench where measurements and runoff sampling were performed. The average plot slope was 0.134 m m^{-1}, ranging from 0.124 m m^{-1} to 0.145 m m^{-1}.

Experimental design

The experimental design was completely randomized. Five treatments were studied with two replications totaling ten experimental plots. The treatments with two replications were: i) no tilled soil with: a) ryegrass crop keeping residues on surface, with high soil cover (100 % of the soil covered at the beginning of the experiment) and minimum soil roughness (HCR); b) vetch crop keeping residues on surface, with high soil cover (90 % of the soil covered at the beginning of the experiment) and minimum soil roughness (HCV); ii) tilled soil with one chiseling transversely to the slope, resulting high roughness and low cover with: a) ryegrass crop, removing the above-ground residues and keeping the root system, resulting high roughness (20.5 mm) (HRR); b) vetch crop, removing the above-ground residues and keeping the root system resulting high roughness (17.4 mm) (HRV); iii) bare and no tilled soil, prepared for two years and chiseled transversely to the slope, with high roughness (14.6 mm) (BHR). The minimum roughness existing in the HCR and HCV treatments resulted from light harrowing performed for incorporating seeds into crop sowing. In the HRR and HRV treatments, the above-ground crop residues were removed after mowing the plants at full bloom stage. Afterward, the soil was chiseled on 13 December 2012, using a two-bar mounted device with 13 tines, spaced 0.25 m, operating at 0.15-m deep to produce high soil roughness.

Measurements

Eight simulated rainfall tests were applied to each treatment using a rotating-boom simulator, driven by hydraulic thrust, covering simultaneously two plots spaced 3.5 m apart. The rains were applied for 90 min, with constant planned intensity of 65 mm h^{-1}, resulting in erosivity of 1,313 MJ mm ha^{-1} h^{-1}. The first test was performed on 17 Dec 2011 and the others respectively on 01 Oct 2012, 07 Feb 2012, 10 Mar 2012, 11 May 2012, 18 Aug 2012, 02 Nov 2012 and 18 Dec 2012, for a year between the first and the eighth tests to reduce soil cover and surface roughness. Rainfall intensity was checked with 20 rain gauges previously installed on soil surface over the coverage area of the rainfall simulator that covered an area of approximately 300 m^2. Between the rainfall tests, the plots were uncovered and subjected to the action of natural rain. Weeds were controlled by application of herbicides whenever necessary.

Surface roughness was determined immediately before soil tillage and prior to each simulated rainfall in the HRR, HRV and BHR treatments. The determinations were always carried out in the same place in the plot, marked by wooden stakes also used to level and support the micro relief meter. Surface roughness was obtained through a photographic record of a 20-bar set, where the bar heights in the photographs, representing the micro relief, were obtained by image interpretation, as described by Bertol et al. (2010). The random roughness index (RR) was calculated using the method proposed by Kamphorst et al. (2000) with no transformation of the data into logarithms or elimination of the extreme values.

Soil cover (SC) by crop residues was determined before each simulated rainfall in the HCR and HCV treatments using the marked rope method (Sloneker and Moldenhauer, 1977) with a 5-m long rope, containing marks at every 0.05 m, where soil coverage was obtained by counting for the total points with residues immediately below the marked points, using two replications per plot. The residue dry mass was also determined immediately before each simulated rainfall, in the HCR and HCV, collecting the residues from an area of 0.36 m^2 in a single position randomly selected in the plot.

During the simulated rain, the runoff instantaneous rate was quantified by the methodology described by Cogo et al. (1984). After starting, runoff was manually measured every five minutes with a graduated cylinder and a chronometer and a runoff sample was collected in a 0.75-L plastic pot to determine the concentration of sediments in runoff (CSR). To determine CSR, we made an average of five readings of runoff instantaneous rate with steady flood, because the erosion rate at this time was not influenced by previous discharge variation.

Surface runoff velocity (RV) was determined 70 min after the rainfall event began, when the measured runoff attained constant flow. The velocity was measured in the six central meters of each plot, marked with stakes (6 m are located 2.5 m above and 2.5 m below the extremities). At the upper extremity, methylene blue dye (2 %) was applied and time required for it to run this distance was recorded, as described by Engel et al. (2009).

Runoff samples to quantify the D_{50} index were collected after 80 min of each simulated rainfall event. The D_{50} index was quantified using a set of sieves with opening sizes of 4.75; 2; 1; and 0.25 mm. In that order, the sieves were placed on a bucket with 2 L capacity, placing the whole set under the flow until the bucket was completely filled. The content of the bucket was taken to the laboratory, where it was filtered through the sieves openings of 0.125; 0.053 and 0.038 mm, also considering the content that passed through the last sieve. All samples were transferred to an incubator at 50 °C for 72 h and then weighed. Thus, the following sizes of sediments were obtained: >4.75; 4.75-2; 2-1; 1-0.25; 0.25-0.125; 0.125-0.053; 0.053-0.038 and <0.038 mm. The D_{50} index was calculated using the procedure adopted by Gilley et al. (1987). This index consists of a numerical value in which 50 % of the sediment mass in the runoff has a size greater than this value and the other 50 % of the sediment mass has a smaller size.

Statistical analysis

The results were analyzed using the statistical package SAS version 9.2 for Windows®, using a mixed model procedure. The Akaike information criterion (Wolfinger, 1993) was used to choose the variance and covariance matrices and detect the main effects such as causes of variance and interaction between them. The rain test effect (time) was considered fixed and the response variables (sediment concentration, runoff velocity and the D_{50} index) were the random effects. The means were compared by DMS of Fischer at 5 % significance level.

Results and Discussion

The average value of random roughness (RR) before the application of soil tillage was 4.1 mm, while after chiseling, RR increased to 17.5 mm (Table 1), agreeing with Bramorski et al. (2012) who also worked with chiseling under natural rainfall. The lowest RR (9 mm) occurred in BHR, while in HRR and HRV treatments, the values were based on the average of the rainfall tests, 12.3 and 12.1 mm, respectively. This difference is explained by the absence of soil cultivation in BHR. The bare soil had lower organic carbon content and was less resistant to soil detachment, agreeing with Martinez-Trinidad et al. (2012).

The highest RR after chiseling was found in the HRR treatment, with 20.5 mm, followed by HRV and BHR treatments, with 17.4 mm and 14.6 mm, respectively (Table 1). The greatest RR observed in HRR after chiseling is due to a higher aggregation provided by ryegrass roots compared to vetch. According to Roisin (2007), grass species increase water stability of soil aggregates compared to leguminous crops. The lower RR in BHR can be explained by the soil less resistance to breakdown (Martinez-Trinidad et al., 2012) and can be related to mechanical soil tillage and raindrop impact, increasing aggregate disruption in comparison with cropped treatments, as discussed by Engel et al. (2009).

RR decreased from the first to the eighth rainfall test in the HRR and HRV treatments, while in BHR, after reducing, RR increased slightly from the seventh test onward due to the formation of rill erosion on soil surface.

Residue biomass in the HCR and HCV treatments, determined immediately before the first test, was respectively of 4.7 and 4.4 Mg ha^{-1} (Table 1). After the first simulated rain test and before the second rain test, both treatments showed small reductions of residue biomass, probably due to the limited contact of this biomass with soil surface. After the second rain test, greater decay occurred in HCV (42 %) compared to HCR (13 %) due to the lower C/N ratio of vetch compared to ryegrass (Gilmour et al., 1998). The greater decay observed in HCR occurred between the seventh and the eighth rain tests with a mass loss of 34 % (percentage of total decay).

Table 1 – Random soil surface roughness (RR) in treatments before tillage (BT) in each simulated rainfall test (T), soil cover with crop residues (SC) and dry mass of crop residues (DM) in a Humic Dystrupept.

Treatments	BT	T 1	T 2	T 3	T 4	T 5	T 6	T 7	T 8	Mean
						RR (mm)				
HRR	4.7	20.5 Aa	15.5 Ab	14.0 Abc	12.3 Abcd	11.1 Acde	10.1 ABde	9.7 Ade	9.0 Ae	12.3 A
HRV	4.6	17.4 ABa	14.7 Aab	11.9 Abc	12.5 Abc	11.4 Ac	10.8 Ac	10.4 Ac	10.2 Ac	12.1 A
BHR	2.9	14.6 Ba	9.6 Bbc	8.3 Bbc	8.4 Bbc	6.6 Bc	7.0 Bc	11.1 Ab	11.1 Ab	9.0 B
Mean		17.5 a	13.3 b	11.4 bc	11.1 cd	9.7 cd	9.3 d	10.4 cd	10.1 cd	
						SC (%)				
HCR	-	100 Aa	98 Ab	97 Ab	99 Aab	89 Ac	57 Ad	44 Ae	31 Af	77 A
HCV	-	90 Bab	91 Ba	86 Bc	87 Bbc	66 Bd	33 Be	17 Bf	10 Bf	60 B
Mean		95 a	95 a	92 b	93 ab	78 c	45 d	31 e	21 f	
						RM (Mg ha^{-1})				
HCR	-	4.7 Aa	4.6 Aa	4.1 Aab	3.1 Abc	2.9 Ac	2.5 Ac	2.2 Ac	0.9 Acd	3.1 A
HCV	-	4.4 Aa	4.2 Aa	2.6 Bb	2.4 Abc	1.6 Bbcd	1.6 Acd	0.7 Bde	0.3 Ae	2.2 B
Mean		4.6 a	4.4 a	3.3 b	2.8 bc	2.3 cd	2.0 de	1.4 e	0.6 f	

HCR: soil cropped and covered with ryegrass residue; HCV: soil cropped and covered with vetch residue; HRR: chiseled soil after ryegrass crop removing above-ground residues and keeping only the root system; HRV: chiseled soil after vetch crop removing above-ground residues and keeping only the root system; BHR: bare and chiseled soil. Capital letters compare the treatments in each rain test, lowercase letters compare rain tests in each treatment (DMS of Fisher).

On average, HCR covered 10 % more soil than HCV from the first to the fourth simulated rain tests (Table 1) ranging from 20 to 25 % between the fifth and the eighth. This difference is associated with a higher DM amount in HCR (Table 1), with its slower decomposition rate and with higher soil cover produced by ryegrass above-ground residues in relation to vetch for the same plant mass (Gilmour et al., 1998).

The lowest concentration of sediments in runoff (CSR) (0.47 g L^{-1}) was found in the HCR treatment (Table 2), followed by the HCV and HRR treatments (5.20 and 6.66 g L^{-1}, respectively), while the highest values were found in the HRV and BHR treatments, 14.55 and 15.23 g L^{-1}, respectively. These crop residues on the surface were effective to reduce CSR compared to bare soil, in agreement with the results found by Gilley et al. (2008), who reported that higher soil cover decreases soil losses. CSR was similar in the HCV and HRR treatments and protection against soil erosion caused by the ryegrass root system in HRR was equivalent to vetch residue cover in HCV. Furthermore, soil surface microrelief produced by chiseling transversely to the slope concentrates erosion in the channels, increasing sediment transport in these treatments, also reported by Zheng et al. (2004).

Comparing the treatments with crop residues on soil surface, CSR was 91 % lower in HCR than in HCV (Table 2), a similar difference was reported by Zheng et al. (2004) using wheat (*Triticum aestivum L.*) residue that was more effective to reduce soil erosion compared maize residue. Among the chiseled treatments, HRR differed from HRV and BHR in terms of CSR. This is related to the greater soil aggregation in soil cropped with

Table 2 – Sediment concentration in runoff (CSR), runoff velocity (RV) and the D_{50} index (D_{50}) in treatments and tests of simulated rain (T) in a Humic Dystrupept.

Tests	Treatments					Mean
	HCR	HCV	HRR	HRV	BHR	
	Sediment concentration (CSR)					
	g L^{-1}					
T1	0.08 Ba	0.33 Bb	0.30 Bc	0.53 Be	2.30 Ad	0.71 e
T2	0.07 Ba	0.43 ABb	0.16 Bc	0.53 Abe	1.05 Ae	0.45 e
T3	0.07 Ca	0.49 Cb	0.32 Cc	3.39 Bd	7.00 Ac	2.25 d
T4	0.07 Ca	0.40 Cb	1.72 Cc	12.61 Bc	17.40 Ab	6.44 c
T5	0.09 Ca	0.84 Cb	0.99 Cc	14.25 Bc	20.27 Ab	7.29 c
T6	0.13 Ca	2.34 BCb	10.80 Bb	24.16 Ab	31.62 Aa	13.81 b
T7	0.64 Ca	16.13 Ba	17.66 Bab	27.71 Ab	17.07 Bb	15.84 b
T8	2.63 Da	20.65 Ca	21.35 BCa	33.19 Aa	25.14 Ba	20.59 a
Mean	0.47 C	5.20 B	6.66 B	14.55 A	15.23 A	
	Runoff velocity (RV)					
	m s^{-1}					
T1	0.027 Bc	0.027 Bd	0.029 Bd	0.029 Be	0.086 Ad	0.040 e
T2	0.026 Bc	0.031 Bd	0.036 Bd	0.056 Be	0.175 Abc	0.065 d
T3	0.048 Dbc	0.047 Dd	0.074 Cc	0.105 Bd	0.162 Ac	0.087 c
T4	0.046 Dbc	0.056 Dcd	0.103 Cb	0.174 Bb	0.239 Aa	0.124 b
T5	0.041 Dbc	0.079 Cc	0.098 Cb	0.168 Bb	0.250 Aa	0.127 b
T6	0.060 Db	0.108 Cb	0.155 Ba	0.139 Bc	0.190 Ab	0.130 b
T7	0.115 Ca	0.173 ABa	0.187 ABa	0.156 BCbc	0.214 Aab	0.169 a
T8	0.143 Ca	0.170 BCa	0.179 ABCa	0.228 Aa	0.209 ABab	0.186 a
Mean	0.063 E	0.086 D	0.108 C	0.132 B	0.191 A	
	D_{50} index (D_{50})					
	mm					
T1	0.04 Bbc	0.12 ABe	0.03 Bde	0.34 ABcd	0.77 Ad	0.26 d
T2	0.05 Cbc	0.55 ABde	0.03 Ce	0.28 BCd	0.84 Ad	0.35 d
T3	0.07 Dc	0.61 Cd	0.03 De	1.44 Aa	1.28 Bc	0.69 c
T4	0.05 Cabc	0.71 BCabcde	0.79 BCcd	1.03 Babc	2.49 Aa	1.01 b
T5	0.16 Dabc	0.77 Ccd	0.18 Dde	1.40 Ba	2.94 Aa	1.09 b
T6	0.10 Cbc	1.28 Ba	1.03 Bc	1.71 Aa	1.10 Bcd	1.04 b
T7	0.18 Cb	0.97 Bbc	1.54 Ab	1.05 Bb	1.49 Ab	1.05 b
T8	0.74 Ca	1.44 BCab	2.35 Aa	1.49 Bab	1.53 Bbc	1.51 a
Mean	0.17 D	0.81 C	0.75 C	1.09 B	1.56 A	

HCR: soil cropped and covered with ryegrass residue; HCV: soil cropped and covered with vetch residue; HRR: chiseled soil after ryegrass crop removing above-ground residues and keeping only the root system; HRV: chiseled soil after vetch crop removing above-ground residues and keeping only the root system; BHR: bare and chiseled soil. Capital letters compare the treatments in each rain test, lowercase letters compare rain tests in each treatment (DMS of Fisher).

grass rather than legumes, also reported by Roisin (2007) and Martinez-Trinidad et al. (2012). Better soil structure increases soil resistance to detachment by raindrop impact and surface flow. The HRV and BHR treatments presented similar CSR due to low influence of vetch on soil aggregation, similar to that of bare soil.

On average, the lowest runoff velocity (RV) was found (Table 2) in the HCR treatment (0.063 m s^{-1}) and the highest in BHR (0.190 m s^{-1}). The low RV in HCR is explained by the formation of a physical barrier by crop residues, increasing flow tortuosity, also observed by Vidal Vázquez et al. (2008). Thus, in HCR, residue decomposition was slower and biomass cover for the same amount of residue was greater than in HCV, increasing soil protection against erosion.

The effect of soil surface conditions on RV was described by an exponential model (Figure 1). This RV reduction is important since it has great influence on the final flow energy, thus, on its capacity to detach and transport coarse soil particles and aggregates (Lambrechts et al., 2013). In bare soil (BHR), the exponential model was weakly adjusted to the data and this treatment had the lowest efficiency to reduce RV due to its low soil aggregate resistance, resulting in fast flattening and sealing of soil surface, which accelerate and increase runoff flow energy, as reported for this soil condition by Bertol et al. (2010).

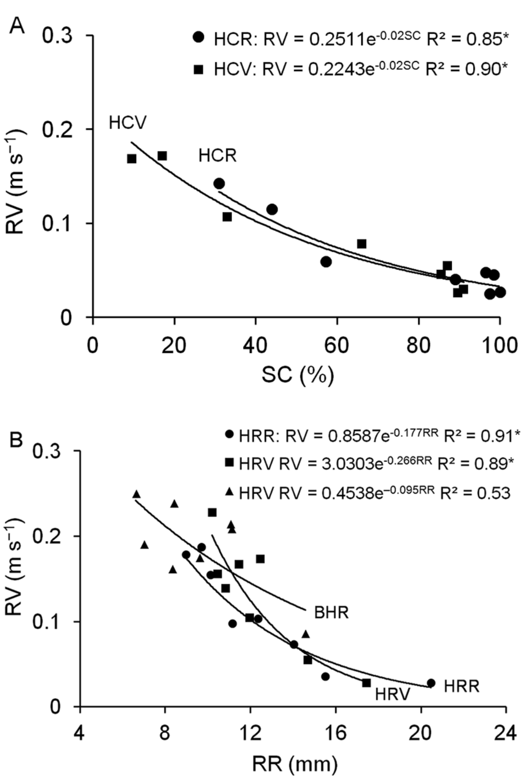

Figure 1 – Relation (a) between runoff velocity (RV) and soil cover (SC) in no-tilled, cropped and covered soil treatments, with ryegrass (HCR) and vetch (HCV) residues and (b) between RV and random soil surface roughness (RR) in chiseled soil, cropped with ryegrass, removing above-ground residues and keeping the root system (HRR); chiseled soil, cropped with vetch, removing above-ground residues and keeping the root system (HRV); and bare and chiseled soil (BHR). These adjustments were based on the average of the rainfall tests.

Crop residues on soil surface in the HCR and HCV treatments were more effective to reduce RV than roughness caused by the action of chisel plow in HRR, HRV and BHR (Table 2, Figure 1). The decrease was on average 48 % in the treatments with residues compared to the treatments with chiseling. This is attributed to the more effective physical barrier to control runoff provided by residues compared to the action of roughness, increasing flow tortuosity, also reported by Vidal Vázquez et al. (2008). Among the residues, ryegrass in the HCR treatment was more effective than vetch in HCV, decreasing RV by 27 % (Figure 1A). This is supported by Lopes et al. (1987) and Gilmour et al. (1998) that reported changes in soil cover due to different crop species, considering the same amount of residue, which was confirmed by the percentage of soil cover in those treatments (Table 1) with similar residue mass.

Comparing the treatments in which the soil was chiseled, the lowest RV values were observed in the cropped soil (Table 2). In the HRR and HRV treatments, RV values were, on average, 37 % lower than in BHR. This result is justified by greater RR kept over time, in the cropped treatments, compared to BHR (Figure 1B). Greater roughness generated higher tortuosity over time in cropped and chiseled soils, slowing runoff flow, as reported by Engel et al. (2009).

The lowest D_{50} index of sediments (0.18 mm) occurred in the HCR treatment, considering the average of the rainfall tests (Table 2), confirming the protective effect of ryegrass residue to dissipate the kinetic energy of raindrops and reduce soil detachment. The fact that the soil was not tilled in this treatment also supports this result. Crop residue cover reduces runoff and increases sediment deposition and it also filters coarse sediments, as reported by Gilmour et al. (1998). However, fine-size sediments transported in the runoff originating from conservational soil tillage are generally richer in nutrients and organic C than coarser sediments are, as reported by Foster et al. (1985), as coarse sediments have less absorption capacity of chemicals, according to Kuhn et al. (2012). Bertol et al. (2003) found greater P concentration and losses in no-tillage in desiccated field. Zhang et al. (2011) found a positive relation between N and P adsorption with clay content in eroded sediments.

Considering the average of the rainfall tests, the greater value of the D_{50} index of sediments (1.56 mm) occurred in the BHR treatment (Table 2). This value is nine-fold greater than that of HCR due to the action of soil cover by ryegrass residue and can be related to the lower aggregation and protection against erosion in the case of bare soil. These conditions increase soil detachment and sediment transport in BHR, as reported by De Baets and Poesen (2010) and Martinez-Trinidad et al. (2012), who found influence of soil cultivation and aggregate stability on soil resistance to erosion. Thus, bare soil allows surface sealing and concentrates runoff in channels, resulting in greater flow velocity in BHR compared to the covered soil (Table 2).

The D_{50} index found in the HCV treatment was similar to that for HRR (Table 2), disagreeing with results reported by Lopes et al. (1987), who found that residues filter coarse sediments in the flow in relation to the tilled soil. This result can be related to the greater soil aggregation caused by ryegrass roots in HRR (Martinez-Trinidad et al., 2012) and by the lower efficiency of vetch residue to filter coarse sediments in HCV, as reported by Barbosa et al. (2010).

Regardless of the management practice, ryegrass generated a smaller D_{50} index of sediments than vetch did (Table 2). Ryegrass decreased D_{50} by 51 % in relation to vetch, when covered treatments (HCR and HCV) and chiseled (HRR and HRV) were grouped in terms of crop type. When considered separately, the HCR and HRR treatments decreased D_{50} by 78 % and 31 % in relation to HCV and HRV, respectively. Lopes et al. (1987) found no difference in the D_{50} index comparing treatments with wheat, maize and soybean under different management practices. However, in a study with oats (*Avena strigosa S.*) and vetch cover crops, Barbosa et al. (2010) found lower D_{50} values in oats compared to vetch crop, regardless of the sowing direction. These authors attributed the small D_{50} under oats crop to its positive effect on soil aggregation due to its high density of fine roots, agreeing with De Baets and Poesen (2010), who reported that increased density of fine roots increased soil aggregation and its resistance to detachment.

The D_{50} index showed an inverse exponential relationship with soil cover and surface roughness (Figure 2), agreeing with Bertol et al. (2010) and Panuska et al. (2008). For the treatments with surface residues, HCR and HCV, the coefficients of determination between the D_{50} index with soil coverage were 0.73 and 0.47, respectively (Figure 2A). For the chiseled treatments, HRR, HRV and BHR, the coefficients of determination between the D_{50} index with soil roughness were 0.72, 0.77 and 0.32, respectively (Figure 2B). The low coefficient of determination in BHR is related to the increase in soil surface roughness, observed in the seventh rainfall test, as previously discussed.

Regardless of the treatment, RV increase was exponentially correlated with the increase in the D_{50} index (Figure 3), showing that RV increased sediment transport capacity, also verified by Bertol et al. (2010). The adjustment degree of these variables was higher in the HRR and HCR treatments in which the D_{50} index was explained by RV 79 % and 88 % respectively, compared to HCV and HRV, where the relations were 50 % and 25 %, respectively. In BHR, the adjustment degree of these variables was also high, indicating that 74 % of the D_{50} index depended on RV.

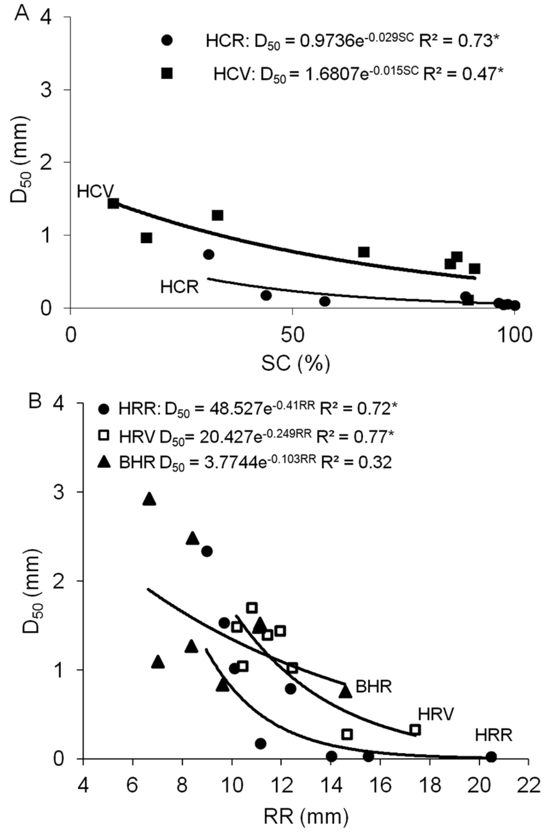

Figure 2 – Relation (a) between the D_{50} index and soil cover (SC) in no-tilled, cropped and covered soil treatments, with ryegrass (HCR) and vetch (HCV) residues and (b) between the D_{50} and random soil surface roughness (RR) in chiseled soil, cropped with ryegrass, removing above-ground residues and keeping the root system (HRR); chiseled soil, cropped with vetch, removing above-ground residues and keeping the root system (HRV); and bare and chiseled soil (BHR). These adjustments were based on the average of the rainfall tests.

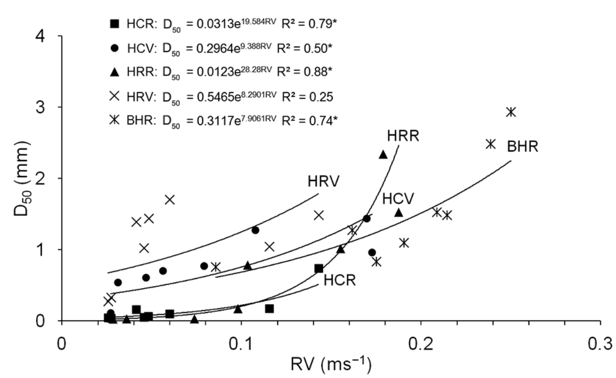

Figure 3 – Relation between the D_{50} index and runoff velocity (RV) in no-tilled, cropped and covered soil treatments, with ryegrass (HCR) and vetch (HCV) residues; in chiseled soil, cropped with ryegrass, removing above-ground residues and keeping the root system (HRR); chiseled soil, cropped with vetch, removing above-ground residues and keeping the root system (HRV); and bare and chiseled soil (BHR). These adjustments were based on the average of the rainfall tests.

Conclusions

Soil cover with crop residues is more effective than surface roughness to reduce runoff velocity, while chiseled soil after removing the above-ground residues and keeping only the root system of crops is more effective than the bare soil chiseled to reduce runoff velocity.

No-tilled and cropped soil with vetch has concentration and D_{50} index of sediments transported by runoff similar to those of chiseled soil cropped with ryegrass, removing above-ground residue and keeping the root system. Chiseled and cropped soil with vetch removing above-ground residue and keeping the root system has a sediment concentration similar to that of bare and chiseled soil.

Runoff velocity and the D_{50} index of transported sediments are exponentially and inversely correlated with soil cover with crop residues and with soil surface roughness, while the D_{50} index of sediments is exponentially and positively correlated with runoff velocity.

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