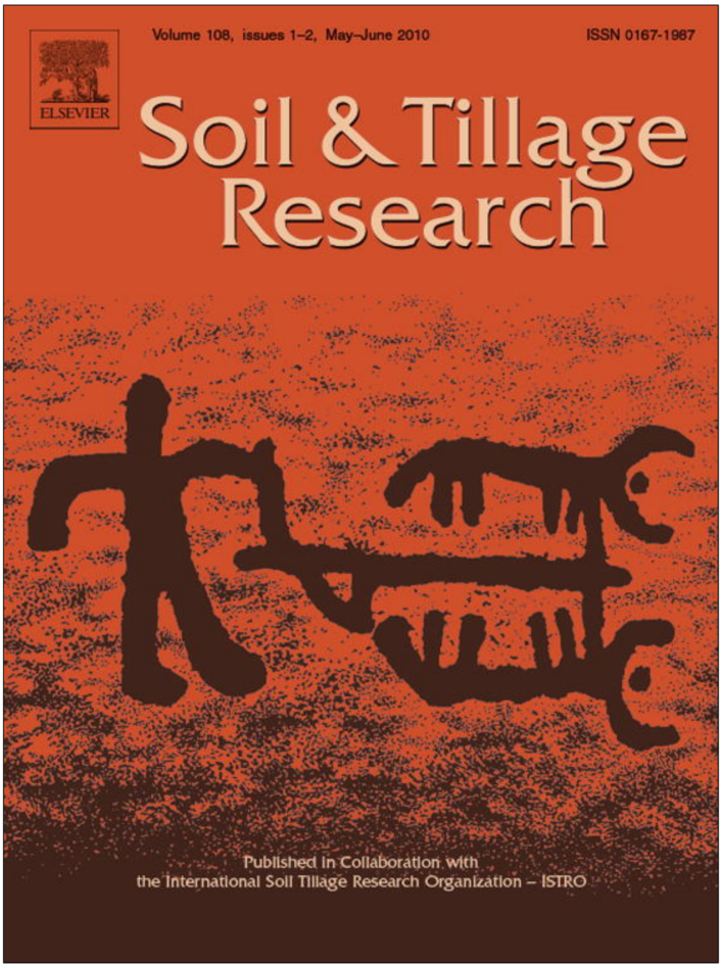

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Effect of crop sequences on soil properties and runoff on natural-rainfall erosion plots under no tillage

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ABSTRACT

The objectives of this work were: (i) to assess the effect of different crop sequences under NT in natural-rainfall erosion plots on different soil properties and runoff, taking as extreme and contrasting references a 10-year pasture and a tilled plot without vegetation, (ii) to analyze the effect on runoff of different categories by volume of rainfalls and (iii) to evaluate the relationship between the intensification of the crop sequence and runoff. The study was carried out between July 2006 and June 2007 (1574 mm of rainfall and 25 runoff events) on six natural-rainfall runoff plots with 3.5% slope and Aquic Argiudoll (Luvic Phaeozem) soil. The treatments were: corn (C) and soybean (S) monocultures, wheat/soybean (W/S) and the W/S phase of a wheat/soybean–corn rotation (W/S–C), pasture (P), and tilled soil without vegetation (L). Surface saturated hydraulic conductivity (K_{hc}) was determined with disk permeameters. Saturated hydraulic conductivity (K_h), bulk density (BD), and pore-size distribution were measured in undisturbed soil cores from 0–0.04 and 0.04–0.08 m soil layers. Cumulative and average runoff and the average runoff coefficient were analyzed while rainfalls were categorized by the magnitude of the rain event. An intensification sequence index (ISI) was calculated as the ratio between the number of months occupied by crops and the total number of months of the year. Surface K_h under field and laboratory conditions (0–0.04 m) was higher in P than in the other treatments (3.3- and 9-fold, respectively) and was similar between crop sequences. Cropping increased BD 26% as compared to P and L. In both layers, BD was negatively associated with K_h and macroporosity, and showed no relation with micro- and mesoporosity. All cropping sequences had reduced macroporosity compared to P, without differences between them. L and S had a higher runoff coefficient than P (6.25-fold), W/S–C and W/S, while C showed an intermediate behavior. Treatments had different runoff coefficients during intermediate and small rainfalls, but not with >70 mm rainfalls. Independently of the rainfall category, S had runoff coefficients similar to those of L, whereas P and crop rotations showed similar losses. Neither the physical nor the hydrological soil properties studied explained the variation in cumulative and average runoff coefficients or those obtained with different rainfall categories. The ISI allowed us to explain cumulative runoff variation, average runoff and average coefficient runoff ($R^2 = 0.9$). Water loss through runoff in our type of soil and climate conditions is more associated with the management of surface cover, mainly the number of month of the year occupied by crops, than with an improvement in the physical properties related to porosity and internal soil water movement.

1. Introduction

In agricultural production, water available for crops is a significant factor in determining crop yields, thus making it necessary to understand the soil water dynamics and the different processes involved. Runoff affects soil water content, water erosion and surface and deep transport of pesticides, nutrients and other solutes (Tebrugge and During, 1999).

Changing soil management practices from a tilled agricultural system to one under no tillage (NT) impacts over the form, magnitude and frequency of stresses imposed on the soil, the placement of crop residues and the population of microorganisms and fauna in the soil (Kay and VandenBygaart, 2002; VandenBygaart et al., 1999). As a consequence, temporal and spatial variations in the structural state of the surface soil under this tillage system affect the hydrological behavior of the soil (Léonard et al., 2006).

Different crop sequences under NT affect the quantity, quality and permanence of crop residues, the amplitude of fallow periods, and the distribution and type of root systems, which condition soil

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structure (Domzal et al., 1991; Benjamin et al., 2007). In fact, modifications generated by the crops or their sequences on the soil-moisture characteristic curve, the surface infiltration rate and the deep water flow have been reported (McVay et al., 2006; Dexter et al., 2001; Sasal et al., 2006).

The Argentine Pampas extend over about 34 Mha (1 Mha = 10^6 ha) of agriculturally useful land, where the main soil-related constraint to cropping is its susceptibility to water erosion (Hall et al., 1992). Important contributing factors are the occurrence of intense rainfalls, particularly in the last two decades there was a slight tendency towards increased summer rainfall, the very long slopes (>500 m) of relatively low gradient (Irurtia et al., 1984), the silty texture of the topsoil and the low permeability of the B horizon of the Argiudolls (Senigagliesi and Ferrari, 1993). In this context, data of the effect of crop sequences and management of surface cover under NT on soil physical and hydrological properties and its relation with runoff induced by different natural-rainfall categories is needed.

The objectives of this paper were to (i) assess the effect of different crop sequences under NT in natural-rainfall erosion plots on different soil properties and runoff, taking as extreme and contrasting references a 10-year pasture and a tilled plot without vegetation, (ii) analyze the effect on runoff of different categories of rainfalls by the magnitude of the rain event and (iii) evaluate the relationship between the intensification of the crop sequence and runoff. This should help to understand the role of agricultural crop sequences under NT on the physical and hydrological properties of the soil and allow identifying the crop sequences that minimize environmental risks.

2. Materials and methods

The study was carried out at the Paraná Experimental Station of the Instituto Nacional de Tecnología Agropecuaria (INTA) of Entre Ríos province, Argentina (31°51′S and 60°31′W) on six natural-rainfall runoff plots with different crop sequences. The region has a subhumid (annual rainfall ≈1000 mm) and temperate climate (annual temperature ≈18.3 °C). Winter temperatures are rarely below 0 °C. The area is covered by a fine, illitic, thermic Aquic Argiudoll (US Soil Taxonomy) of the Tezanos Pinto Series (Luvic Phaeozem, WRB). The texture of the A horizon is silty loam with 27 and 66% of clay and silt, respectively (Plan Mapa de Suelos, 1998).

Rainfall erosion plots (4 m × 25 m) have a natural slope of 3.5% and were designed for volume measurement of water and sediments transported by surface runoff (Fig. 1). Plots were conventionally tilled for 20 years and thereafter four crop sequences were implemented continuously for 15 years under NT. The treatments analyzed were: corn (C) and soybean (S) monocultures, wheat/soybean (W/S) and the W/S phase of a wheat/soybean–corn rotation (W/S–C), pasture (P) and tilled soil without vegetation (L). Sowing, pesticides applications and wheat and soybean harvesting operations used agricultural machinery. The plot under tilled soil without vegetation (L) was annually removed in March and October, and weeds were chemically controlled with Glyphosate 46% in all the plots.

2.1. Measurements

After each runoff-producing rainstorm, runoff volume was measured in the collecting tank at each plot outlet between July 2006 and June 2007. A total of 25 runoff events were recorded and the total rainfall for that period was 1574 mm (50% higher than the long-term average for the same period) (Fig. 2). Cumulative and average runoff were analyzed and categories of rainfalls were divided by the magnitude of the rain event into large (>70 mm), intermediate (41–69 mm) and small (<40 mm) (Fig. 2). The runoff coefficient was calculated as the ratio between runoff and rainfall (mm mm^{-1}) for each rain event.

Fig. 1. Runoff plots of INTA EEA Paraná.

In 2008, 12-cm diameter disk permeameters were used to characterize steady-state infiltration rates at 0 cm tension. Infiltration was measured in five randomly selected sites at each plot. A 5-mm layer of sand was spread on the exposed area and leveled to ensure proper contact with the plate. These measurements were performed on the soil surface for 60 min to reach steady-state conditions (Ankeny, 1992). Surface saturated hydraulic conductivity (K_{hc}) was estimated through the measurement of steady-state infiltration, solving Wooding equation (1968), using the White and Sully (1987) method (Logsdon and Jaynes, 1993).

Twenty-four hours after infiltration measurements undisturbed soil cores (0.03 m long and 0.05 m in diameter) were taken from the same sites (five replications) at two depths (0–0.04 and 0.04–0.08 m) to determine bulk density (BD) (Blake and Hartge, 1986), saturated hydraulic conductivity (K_h) (by the constant head method, Klute and Dirksen, 1986) and pore-size distribution. Cores in the sampling cylinders were slowly saturated under vacuum over 24 h, to minimize structural breakdown, and subsequently brought to −6 kPa matric potential using Tempe pressure cells and −33 kPa matric potential using pressure plates (Klute and Dirksen, 1986). Soil water retention was expressed in terms of volumetric water content using bulk densities for the conversion. Pore-size distribution was calculated using the relationship between soil water content and matric potential (Hillel, 1980). Soil pores were classified as: micropores (<10 μm in diameter), mesopores (10–50 μm), and macropores (>50 μm).

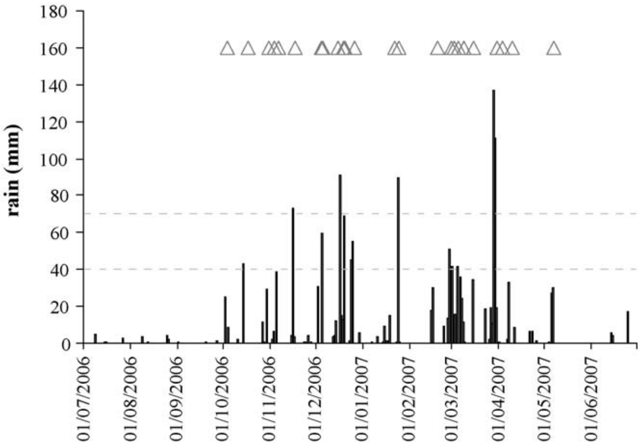

Fig. 2. Daily rainfall events occurred in the study period (columns) and runoff events (symbol △). Dotted line shows thresholds of rainfalls categorized by volume.

Table 1
Effect of crop sequence on average K_{hc}, K_h and BD at two soil depths (0–0.04 m and 0.04–0.08 m). Different letters indicate significant differences among treatments ($p < 0.05$).

Treatments	Surface	0–0.04 m		0.04–0.08 m	
	K_{hc} (mm h^{-1})	K_h (mm h^{-1})	BD (g cm^{-3})	K_h (mm h^{-1})	BD (g cm^{-3})
S	27.36 b	29.76 b	1.31 a	4.3 b	1.43 a
C–W/S	34.82 b	30.16 b	1.26 a	77.9 ab	1.40 a
W/S	23.26 b	6.32 b	1.40 a	2.9 b	1.43 a
C	26.79 b	48.70 b	1.33 a	24.1 b	1.42 a
P	87.23 a	374.56 a	1.03 b	291.2 a	1.11 b
L	18.41 b	89.15 b	1.08 b	96.3 ab	1.14 b

Dry matter production was quantified at harvest by hand harvesting aerial biomass from 1.4 m at three positions in each plot. A value of 0 kg of dry matter by surface unit was assigned to the L treatment. An intensification sequence index (ISI) was calculated as the ratio between the months occupied by crops and months of the year (e.g., P = 12/12 = 1; S = 4.5/12 = 0.38; C = 5.5/12). This index is similar to the one described by Farahani et al. (1998) that expresses the number of crops per year in a given sequence.

2.2. Statistical analysis

The effects of crop sequences on runoff and soil properties were analyzed by their variances with the GLM (General Linear Models) procedure of SAS (SAS, 1989). Least significant difference (LSD) multiple comparison test ($p < 0.05$) was used. Correlation between values of K_{hc} and K_h and linear regressions between variables associated with water movement and the soil properties analyzed and between crop dry matter and time occupied by different sequences and runoff were carried out using the CORR (Correlation Coefficient) and REG (Linear Regression Model) procedures of SAS (SAS, 1989).

3. Results and discussion

3.1. Saturated hydraulic conductivity

Surface saturated hydraulic conductivity under field and laboratory conditions (0–0.04 m) was higher in pasture than in the other treatments and was similar among crop sequences (Table 1). However, at 0.04–0.08 m, K_h of both the tilled soil and the W/S–C rotation not differed of the pasture. The different values obtained at both depths could be related to reported stratification of soil properties such as organic matter (Franzluebbers, 2003) and moisture retention (Díaz-Zorita et al., 2004) due to the NT system.

Although hydraulic conductivity is considered an indicator of water movement and soil changes generated by use, in this work neither surface K_h nor K_{hc} appeared as differentiation variables of treatments under NT. Benjamin et al. (2007) found similar results in a silt loam soil of the USA, but no differences in water movement between different rotations under NT. These authors also reported a higher value of K_{hc} in a pasture than in other agriculture treatments, due to the lower traffic of agricultural machinery and to high root durability, both of which increase soil stability and soil pore continuity for the water flow.

In this work, there was a significant positive association between K_{hc} and K_h ($p < 0.01$, $r = 0.72$). However, average values of these properties differed, being K_h 2.5-fold higher than K_{hc}. Arya et al. (1998) also found a positive association between field and laboratory-measured data; however, K_h was two to three orders of magnitude lower than the field-measured values. These authors attributed such difference to soil compaction during core extraction under high moisture soil condition. In our work, laboratory-measured values were higher than those recorded in the field and presented high variability. This could be due to the 0.02-m constant hydraulic charge imposed in laboratory tests and to soil disruption during sampling and transportation. In addition, when cylinders are inserted into the soil and are used to force quasi one-dimensionally flow, platy surface structure is usually broken and thus strongly affect infiltration rates (Léonard et al., 2006). Treatments S and W/S–C had similar values of K_{hc} and K_h (0–0.04 m), while W/S showed low values of K_h.

Plots with crops showed greater BD than P and L for both the 0–0.04 and 0.04–0.08 m layers ($p < 0.05$) and no differences were found between these two last treatments. As a result, root growth in pasture and soil tillage seems to have a similar effect on this property. In treatments that included annual crops, the higher densification of the A horizon could be related to the use of agricultural machinery for sowing and harvesting. There was a negative association between BD and K_h at the 0–0.04 m and 0.04–0.08 m depths ($r = -0.67$ and -0.59, respectively; $p < 0.01$) and BD did not allow differentiating within crop treatments.

3.2. Pore-size distribution

There was no effect of crop sequences (W/S and W/S–C) on macropores (0–0.04 m), but there were differences between soybean monoculture and treatments L and P ($p < 0.05$) (Fig. 3). The reduced macroporosity under NT compared to the tillage treatment may be produced not only by the destruction or collapse of pores due to soil compression, but also by the inability of silty soils to generate structural pores (Ringrose-Voase, 1991) due to a low proportion of smectite clays in the soil matrix. The percentage of mesopores was greater ($p < 0.05$) in the W/S–C rotation than in the other treatments, except for the soybean monoculture. On the other hand, the percentage of micropores in the crop treatments was similar to that in pasture, except for the soybean monoculture, where the percentage of micropores was similar to that in the tilled plot.

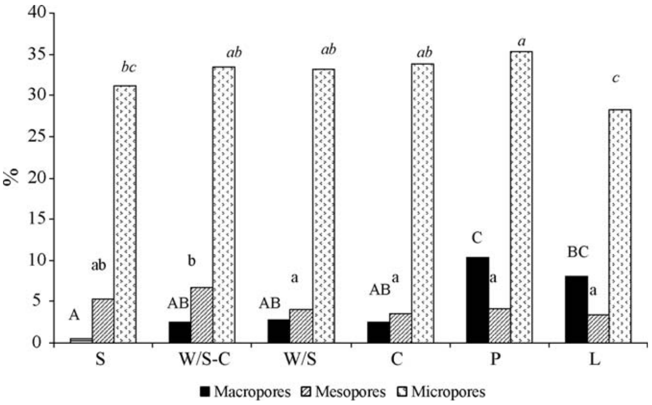

Fig. 3. Average pore-size distribution of 0–0.04 m layer. Different letters indicate significant differences between treatments for each category of pores ($p < 0.05$).

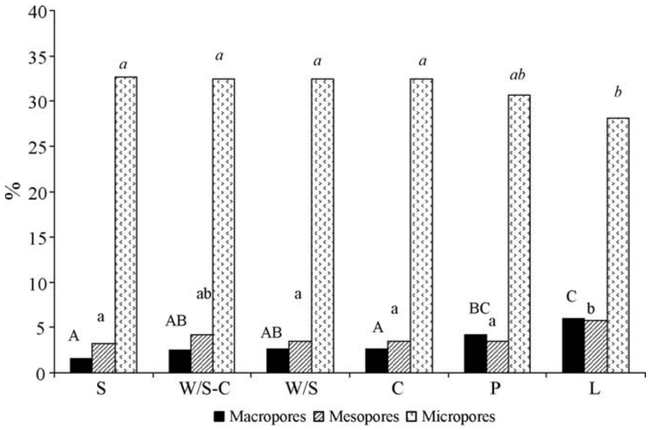

Fig. 4. Average pore-size distribution of 0.04–0.08 m layer. Different letters indicate significant differences between treatments for each category of pores ($p < 0.05$).

Table 2
Effect of crop rotation on average runoff, cumulative runoff and average runoff coefficients. Different letters indicate significant differences among treatments ($p < 0.05$).

Treatments	Cumulative runoff (mm)	Average runoff (mm)	Average runoff coefficient (mm mm^{-1})
S	328	17.40 a	0.24 a
W/S–C	178	7.14 a	0.08 b
W/S	180	6.25 a	0.07 b
C	339	14.36 a	0.19 ab
P	48	2.52 a	0.04 b
L	413	17.90 a	0.26 a

Table 3
Average runoff coefficient of each crop rotation categorized by natural-rainfall size. Different letters indicate significant differences between treatments ($p < 0.05$).

Treatments	Runoff coefficients		
	Large rainfalls (>70 mm)	Intermediate rainfalls (41–69 mm)	Small rainfalls (<40 mm)
S	0.31 a	0.34 a	0.06 ab
C–W/S	0.21 a	0.02 b	0.01 b
W/S	0.14 a	0.04 b	0.03 b
C	0.27 a	0.20 ab	0.10 ab
P	0.07 a	0.02 b	0.03 b
L	0.33 a	0.31 a	0.15 a

Comparison between S and P showed that S presented less macro- and microporosity. Changes in soil pore-size distribution caused by compaction are characterized by an increase in the percentage of pores of small and intermediate diameters in detriment of larger pores (Andriulo and Rosell, 1988; Ankeny et al., 1990; Rasmussen and Arshad, 1999). Therefore, these differences might be associated with a biological porosity formed by roots and soil organisms. In agreement with this, Benjamin et al. (2007) reported that the action of perennial pasture is more effective for continuous and stable pore creation than that of annual crops.

In coincidence with the surface layer, the 0.04–0.08 m layer showed no effect of crop sequences on macropores and the tilled soil showed higher values similar to those of the pasture (Fig. 4). In both layers, BD was negatively associated to macroporosity ($r = -0.80$ and $r = -0.65$, for the 0–0.04 and 0.04–0.08 m layers, respectively; $p < 0.01$) and showed no relation with micro- and mesoporosity.

3.3. Runoff

The first runoff of the study period was recorded in October. High rains (289 and 357 mm over the long-term monthly rainfall) were recorded in December and March. The rainfall and runoff events occurred in the study period are shown in Fig. 2. As frequency of rainy days is associated with monthly rainfall (Hall et al., 1992), the highest values of daily rainfalls and the highest frequency occurred in December and March.

Corn and soybean monocultures presented a cumulative loss of water 6-fold greater than the pasture and similar to the tilled treatment (Table 2). Frye et al. (1985) obtained similar results with these crops but with conventional tillage. Crop rotations had intermediate and similar losses. Ghidey and Alberts (1998) obtained similar results comparing runoff of soybean and corn under no tillage with a tilled and uncovered soil.

The average runoff was similar for all treatments; however, the runoff coefficient was more sensitive than the water exported out of the plots to show the effect of the different crop sequences (Table 2). In this way, the tilled and uncovered soil and the soybean monoculture lost a higher proportion of rain water through runoff ($p < 0.05$), while pasture, W/S–C and W/S retained more rain water. Corn monoculture showed an intermediate behavior.

Table 3 shows the results of the average runoff coefficient in different plots, categorized by volume of natural rainfalls. Blanco-Canqui et al. (2004) analyzed runoffs from plots with different uses, and improved the results by categorizing natural rainfalls by the storm size. The humid period analyzed allowed the classification of the rain events by their magnitude. Around 30% of the rain events during the study period exceeded 70 mm, 35% were 40–70 mm and 35% were <40 mm. Treatments had different runoff coefficients during intermediate and small natural rainfalls, but showed no differences with >70 mm of rainfall (Table 3). Intermediate rainfalls repeated a pattern of differentiation between treatments similar to that of the analysis of all the rainfall data. In this way, the different crop sequences affected runoff, depending on the category of natural rainfall considered. However, independently of the rainfall category, soybean monoculture had runoff coefficients similar to those of tilled soil, whereas the pasture and crop rotations showed similar losses.

The most important improvement of a crop sequence on the sustainability of the system, especially in soils with decreased water storage capacity due to erosion, is runoff reduction and the consequent increase in infiltration (Frye et al., 1985). In this study, we found that monocultures (especially soybean monoculture) and soil tillage with direct exposure to raindrop impact produced similar runoff losses. However, crop sequences (W/S and W/S–C) behaved as pastures during different natural rainfalls.

An important issue to meet the requirements of sustainable intensification in the Argentine Pampas is the design of cropping sequences oriented to use the available resources during the winter season, since our agriculture largely relies on summer crops (Caviglia and Andrade, 2010). In this sense, crop sequences that included a winter crop (wheat) presented a runoff coefficient similar to that of pasture.

3.4. Relationship between runoff and other variables

Numerous studies agree that no tillage promotes higher soil surface infiltration rates, higher soil water storage, and lower runoff losses than tillage (Tebrugge and During, 1999). In our work, neither the physical nor the hydrological variables studied (BD, K_h, K_{hc}, and macro-, meso- or micropores) explained the variation in cumulative and average annual runoff coefficients or those obtained with different rainfall categories.

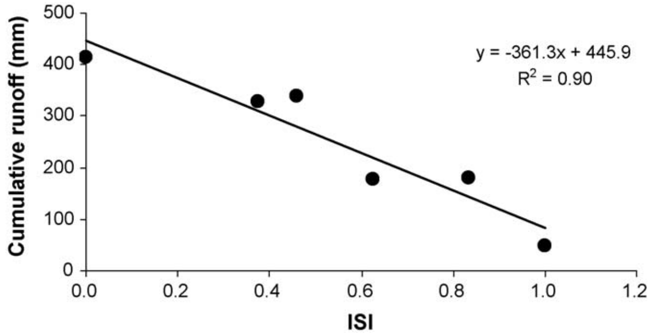

Fig. 5. Linear regression between the intensification sequence index (ISI) and cumulative runoff (mm).

In the same plots as those studied in the present work, Sasal et al. (2008) measured structural stability by MWD (Le Bissonnais et al., 2002) and organic carbon content of the 0–0.12 m layer. These authors found association between the variables and cumulative runoff, probably due to its effect over soil resistance to surface seal formation. In spite of this, we could not find significant correlations between such properties and K_{h} or K_{hc} in this work.

Although the role of crop residue cover under NT on the protection of the soil surface from the impact of raindrops avoiding surface sealing is frequently recognized, our results showed that the variation of the cumulative runoff and the runoff coefficients categorized by rainfall magnitude were not explained by the dry matter production (results not shown). In fact, total dry matter production was: 21,382, 5895, 8670 and 6214 kg ha^{-1} year^{-1} for C, S, W/S phase of W/S–C rotation and W/S, respectively. In this way, corn monoculture with 3-fold more dry matter production had runoff losses comparable to those of soybean monoculture with a low residue input and a low C:N ratio. These results suggest that to reduce water runoff, the period of the year occupied by crops is more important than the amount of surface residues.

The ISI allowed us to explain cumulative runoff variation ($R^2 = 0.90$, $p < 0.01$) (Fig. 5). Similar results were found when relating this index with the average runoff and the average runoff coefficient (results not shown). The analysis of the rainfall categories indicated that ISI explained 90, 73 and 71% of runoff coefficient variation in large, intermediate and small rainfalls, respectively ($p < 0.01$). The ISI was a good indicator of water loss by runoff, but was not related to the soil physical variables analyzed. As a consequence, 70% of rainfalls that produced runoff during the study period, classified as intermediate and small, presented different runoff volumes depending on the period of the year occupied by crops in each treatment and irrespectively of the quantity of surface residues they produced.

4. Conclusions

The crop sequences under NT analyzed presented important differences both in their cumulative runoff (tilled soil > monocultures > crop rotations > pasture) and its relation with the natural rainfalls occurred during the study period. However, crop sequences did not impact on the hydrological soil properties. Pasture was the only treatment that had a surface water dynamics different from that of the other treatments, and better physical conditions and hydrological soil properties. Monocultures presented water losses similar to the tilled treatment and 6-fold higher than pasture independently of the dry matter input, due to long fallow periods without crops, which favored water loss by runoff. In this way, runoff in the type of soil and climate conditions analyzed is more associated with the management of surface cover rather than with an improvement in the physical properties related to porosity and internal soil water movement. In consequence, lower water losses by surface runoff in treatments W/S and W/S–C were not related to the amount of crop residues on the soil surface but mainly to crop duration. The analysis of natural-rainfall size categories showed that when rainfalls exceeded 70 mm, runoff was similar in all treatments, independently of the soil conditions and the amount of residue cover. Most rainfalls at this location are of less than 70 mm, and under these conditions, crop sequences that included a winter crop (wheat) present a runoff coefficient similar to that of pasture.

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