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Nutrient and Organic Carbon Losses, Enrichment Rate, and Cost of Water Erosion

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ABSTRACT: Soil erosion from water causes loss of nutrients and organic carbon, enriches the environment outside the erosion site, and results in costs. The no-tillage system generates increased nutrient and C content in the topsoil and, although it controls erosion, it can produce a more enriched runoff than in the conventional tillage system. This study was conducted in a Humic Cambisol in natural rainfall from 1997 to 2012 to quantify the contents and total losses of nutrients and organic C in soil runoff, and to calculate the enrichment rates and the cost of these losses. The treatments evaluated were: a) soil with a crop, consisting of conventional tillage with one plowing + two harrowings (CT), minimum tillage with one chisel plowing + one harrowing (MT), and no tillage (NT); and b) bare soil: one plowing + two harrowings (BS). In CT, MT, and NT, black oat, soybean, vetch, corn, turnip, and black beans were cultivated. Over the 15 years, 15.5 Mg ha^{-1} of limestone, 525 kg ha^{-1} of N (urea), 1,302 kg ha^{-1} of P$_2$O$_5$ (triple superphosphate), and 1,075 kg ha^{-1} of K$_2$O (potassium chloride) were used in the soil. The P, K, Ca, Mg, and organic C contents in the soil were determined and also the P, K, Ca, and Mg sediments in the runoff water. From these contents, the total losses, the enrichment rates (ER), and financial losses were calculated. The NT increased the P, K, and organic C contents in the topsoil. The nutrients and organic C content in the runoff from NT was greater than from CT, showing that NT was not a fully conservationist practice for soil. The linear model y = a + bx fit the data within the level of significance (p≤0.01) when the values of P, K, and organic C in the sediments from erosion were related to those values in the soil surface layer. The nutrient and organic C contents were higher in the sediments from erosion than in the soil where the erosion originated, generating values of ER>1 for P, K, and organic C. The value of the total losses of nutrients in the form of triple superphosphate fertilizer, potassium chloride, and urea and limestone by water erosion was higher in CT than in NT. For triple superphosphate, the cost of erosion losses was 29 % higher in NT than in CT, while in urea and limestone, the effectiveness of NT in reducing costs was 65 and 50 %, respectively.

Keywords: soil erosion, soil and water losses, nutrient losses, cost of erosion.

INTRODUCTION

An increase in erosion has compromised the safety of life on earth, especially as of the late 20th century (Amundson et al., 2015). Soil erosion from water (water erosion) is influenced by rainfall, soil, topography, and conservation practices and especially by soil cover and management (Ellison, 1947; Wischmeier and Smith, 1978), which depend on the manner of mechanical soil tillage (Schick et al., 2016). An increase in tillage intensity degrades the physical properties of the soil, reduces water infiltration, and increases water erosion, which impoverishes the soil in its place of origin and contaminates the environment outside that site (Koski-Vähälä and Hartikainen, 2001; Hart et al., 2004; Bertol et al., 2007b; Shigaki et al., 2007; Coletti et al., 2010). Erosion also implies costs, due to loss of nutrients and soil amendments (Bertol et al., 2007a; Andrade et al., 2011; Duan et al., 2011; Pugliesi et al., 2011; Dechen et al., 2015).

In the absence of mechanical tillage, the soil surface cover remains and gradients of nutrients and organic matter form in the depth in the soil (Eltz et al., 1989; Andrade et al., 2012). The absence of tillage in no-tillage (NT) increases the content of some nutrients and organic matter on the soil surface in relation to the subsurface. However, conventional tillage (CT) of the soil homogenizes the distribution of nutrients and organic matter in the tilled layer, whereas in minimum tillage (MT) these variables have intermediate values in the soil in the surface layer (Andrade et al., 2012). According to these authors, the fertilizers applied and crop residues maintained on the soil surface due to absence of tillage in NT are responsible for these conditions. With water erosion, increased losses of nutrients and organic matter occur since these nutrients and organic matter are concentrated at the soil surface (Bertol et al., 2007b; Dantas and Monteiro, 2010; Pugliesi et al., 2011; Dechen et al., 2015).

The NT causes a decrease in total losses of nutrients and organic matter by erosion, due to a decrease in total losses of soil and water compared to CT, despite higher contents of these nutrients and organic matter in runoff water in NT (Avalos et al., 2009; Dantas and Monteiro, 2010; Pugliesi et al., 2011). The effectiveness of the NT system in controlling the loss of plant nutrients and organic matter is unsatisfactory, due to their high contents present in the runoff water and in the eroded sediments (Barbosa et al., 2009). Phosphorus constitutes a source of contamination outside the place of origin of erosion, causing eutrophication of waters (Sharpley et al., 2001; Hart et al., 2004). These elements added to the soil to supplement fertility are easily lost through water erosion, and organic matter is lost as well, especially in the NT management system (Dantas and Monteiro, 2010; Pugliesi et al., 2011), which shows the low efficiency of NT in control of these losses by erosion.

The enrichment rate (ER) is represented by a numerical value resulting from the ratio between the content of a given chemical element in the sediments from erosion and the content in the soil from which the erosion originated (Langdale et al., 1985). According to these authors, enrichment with nutrients and organic C is attributed in part to the fact that sediments transported by the runoff are of small diameter and/or low density (clay and organic matter) in relation to the diameter and/or density of the sediments that remain in the soil (silt and sand) at the erosion site, due to the selectivity of erosion. The mineral and organic fraction strongly adsorbs chemical elements, and this fraction is easily removed by erosion due to its low density, which explains the higher organic C content in the sediments from erosion than in the surface layer of soil where the erosion occurred (Silva et al., 2005). Enrichment is manifested when the ER is >1 and, when <1, enrichment has not occurred. The ER in nutrients, particularly P, is an indicator of the contamination potential erosion has in the environments of erosion deposition. Despite this importance, very few studies have been conducted in Brazil with a view to determining the ER of nutrients in agricultural areas (Barbosa et al., 2009). In other countries, this issue is studied more intensively (Koski-Vähälä and Hartikainen, 2001; Sharpley et al., 2001; Hart et al., 2004; Shigaki et al., 2007; Lewis and Wurtsbaugh, 2008; Coletti et al., 2010).

There is a positive linear correlation between the P, K, and organic C contents contained in the eroded sediments and the contents existing in the 0.00-0.02 m layer of soil at the erosion site, thus establishing ER (Schick et al., 2000). The reasons for this type of ratio, according to these authors, are based on the fact that the nutrients and organic matter, concentrated on the soil surface in NT, are easily transported by the runoff, since erosion is selective (Langdale et al., 1985). Therefore, the less dense and smaller fractions are more easily transported (Silva et al., 2005). In these studies, authors also found that, in general, in the sediments and in the runoff water, ER values for calcium and magnesium were <1, unlike P, K, and organic C, for which the ER values were >1.

The total losses in regard to plant nutrients and limestone by water erosion represent cost (Bertol et al., 2007b; Duan et al., 2011; Dantas and Monteiro, 2010; Pugliesi et al., 2011; Dechen et al., 2015) because they need to be replaced in the crops through use of fertilizers (Pugliesi et al., 2011), raising the cost of agriculture. This cost is usually not taken into account by farmers, due to lack of knowledge. The cost of these losses depends on the level of the elements contained in the runoff (water and sediments) and the total amount of runoff (Bertol et al., 2007b). In studies carried out in other countries, it was shown that the total cost of these losses was higher in CT than in NT (Hart et al., 2004). In Brazil, some studies showed that this value was greater in NT than in CT (Bertol et al., 2007b), others showed the opposite (Dantas and Monteiro, 2010), and others showed that increased soil cover decreased the amount of losses (Dechen et al., 2015), thus establishing a contradiction. Knowledge of the cost of nutrient losses through erosion is important in helping convince farmers to adopt effective conservation practices to reduce erosion and its cost.

The hypothesis is that no-tillage causes an accumulation of nutrients and organic C in high concentrations in the soil surface layer due to the absence of tillage, the application of fertilizers on the surface, and the presence of crop residues on the surface, and that these contents are higher in no-tillage than in conventional tillage. This condition causes nutrient and organic C contents to be higher in the erosion sediments than in the soil from which they originate, and thus the contents in the runoff of no-tillage may be higher than in conventional tillage. In management systems both, the P, K, and organic C enrichment rates are >1 and the ratio of the contents of these elements in the soil and sediments follows a positive linear model. Furthermore, the hypothesis can be formed that the cost of total nutrient losses in the form of fertilizer and limestone is higher under conventional tillage than in no-till because the total losses of water and sediments are greater in the conventional system.

The aim of this study was to quantify the contents of P, K, Ca, Mg, and organic C in the soil, and the contents and total losses in the sediments and in the runoff water resulting from erosion under different management systems, as well as calculate the enrichment rate and the cost of these losses.

MATERIALS AND METHODS

The study was conducted under conditions of natural rainfall for 15 years at Lages, state of Santa Catarina, Brazil, from May 1997 to October 2012 in a region with geographical coordinates 27° 47' 13" S and 50° 18' 23" W and altitude of 923 m, within a long-term water erosion experiment that began in 1988. The climate is Cfb, humid mesothermal, according to the Köppen classification system (Alvares et al., 2013). Annual rainfall is 1,533 mm, 824 in the spring/summer and 709 in the autumn/winter, while the annual erosivity is 5,033 MJ mm ha^{-1} h^{-1}, 3,254 in the spring/summer and 1,779 in the autumn/winter, at the site of the experiment (Schick et al., 2014). The soil is a *Cambissolo Húmico Alumínico léptico* (Santos et al., 2013), a Humic Cambisol according to the IUSS/WRB (2006) classification. The Ap horizon (0.0-0.2 m) of the soil contains 180 g kg^{-1} of sand, 420 g kg^{-1} silt, 400 g kg^{-1} clay, and 40 g kg^{-1} of total organic C and the soil bulk density is 1.30 Mg m^{-3}. At the site of the experiment, the area has an average slope of 0.102 m m^{-1}.

The soil management treatments, with two experimental units, or plots, per treatment, randomly distributed were a) soil with a crop: one plowing + two harrowings, called conventional tillage (CT); one chisel plowing + one harrowing, called minimum tillage (MT); without tillage, called direct seeding or no-tillage (NT); and b) bare soil without a crop (control) - one plowing + two harrowings (BS). In the CT, MT, and NT treatments, soil tillage was carried out with operations longitudinal to the slope, in which oats (*Avena strigosa)*, soybeans *(Glycine max)*, vetch (*Vicia sativa*), corn (*Zea mays*), turnip (*Raphanus sativus*), and black beans (*Phaseolus vulgaris*) were grown in rotation.

The soil pH was adjusted with dolomitic limestone at the time of setting up the experiment in October 1988 with 12 Mg ha^{-1}; and in October 1992, an additional 3.5 Mg ha^{-1} of dolomitic limestone was applied, except at the site where the BS treatment was set up. Over the period of this study (1997-2012), we applied 525 kg ha^{-1} of N (urea), 1,302 kg ha^{-1} of P_2O_5 (triple superphosphate), and 1,075 kg ha^{-1} of K_2O (potassium chloride), distributed in the spring-summer crops, without fertilizer in autumn-winter. In NT, fertilizers were applied by broadcast on the soil surface without incorporation, and in CT and MT, they were incorporated and partially incorporated into the soil by tillage, respectively.

The experimental unit, or plot, had a useful area of 77.35 m^2, with dimensions of 22.1 m down the slope and 3.5 m width. Each plot was delimited at the upper end and at the sides by galvanized sheeting of 0.2 m height, with 0.1 m stuck into the ground. The bottom end of the plot had a gutter to collect runoff, connected to a pipe carrying the runoff water to the first tank, a sedimentation tank, located 6 m below the plot. This tank was connected through a "Geib" type runoff divider with nine windows to a second tank, a storage tank.

Collecting runoff samples in tanks for each of the crops and their processing in the laboratory to quantify the total losses of sediments and water, and the contents of P, K, Ca, Mg, and organic C in sediments, as well as the P, K, Ca, and Mg contents in the water, was carried out according to the method proposed by Cogo (1978). Collected at each occurrence of erosive rainfall, the sediment samples were dried at 60 °C and stored in plastic pots until the end of the cycle of each of the crops, while the water samples were placed in a refrigerator. Thus, a sample of sediments and water from each plot was formed for each crop, for a total of 14 samples in autumn/winter cropping and 15 in spring/summer cropping.

At the end of each crop cycle, disturbed soil samples were collected in the 0.00 to 0.025 m layer in each plot, totaling 14 samples in the autumn/winter cropping and 15 in the spring/summer cropping. These samples were dried at 60 °C, ground, passed through a 2 mm mesh sieve, and packed for later analysis. Samples were collected only in that layer of the soil because water erosion occurs predominantly on the soil surface in experimental plots of this type.

Phosphorus and K were determined in the samples of eroded sediments and soil through double acid extraction (Mehlich-1); P was determined by absorbance on a spectrophotometer and K by flame photometry. In these samples, the contents of Ca^{2+} and Mg^{2+} were extracted with 1 mol L^{-1} KCl and determined by atomic absorption; and organic C was determined by oxidation in acid medium and titration with $FeSO_4$ by the Walkley-Black method. This was followed by the procedures described in Tedesco et al. (1995). In the samples of runoff water, the contents of soluble P, K, Ca, and Mg were directly determined by atomic absorption.

The organic C content was multiplied by 1.724 to express it in organic matter. From the P and K contents, the amounts of triple superphosphate fertilizer and potassium chloride were calculated, and with the Ca+Mg contents, the amount of limestone.The amount of urea was calculated based on the average concentration of N contained in the humic fraction of organic matter, as shown in Souza and Melo (2000). The amounts of these fertilizers and of the limestone were obtained by multiplying the contents of P, K, Ca, Mg,

and N in the sediments and in the water from erosion by the quantities of sediments and water lost by erosion. Furthermore, we calculated the cost of fertilizers and limestone, taking into account the prices of these inputs on the Brazilian market in February 2016.

We verified the possibility of normality of distribution of the P, K, Ca, Mg, and organic C contents in the soil and sediments, and of P, K, Ca, Mg contents in the water from erosion by the Kolmogorov-Smirnov test (p≤0.05); when the distribution was not normal, the values were transformed into log (y). The effect of treatments on those contents was assessed by the t test (p≤0.05). Multiple comparisons were carried out by orthogonal contrasts of the F test using a mixed model to explain the effect of the treatments on the contents of the elements and the organic C. To do so, the treatments were considered as the fixed effect factor and the crops as repetition over time, with the averages being compared by univariate and multivariate contrast, as follows: BS × (CT, MT, NT); CT × (MT, NT); and MT × NT. By means of linear regression, the P, K, and organic C contents were correlated in the 0-0.025 m layer of the soil with contents in the sediments using the model $y = a + bx$. The regression coefficient of the equations of adjustment represented the enrichment rate (ER) values. The ER was addressed in the discussion of results also as resulting from the ratio between the contents of P, K, and organic C in the sediments and in the soil. The data on losses of sediments and on P, K, Ca, Mg, and organic matter in the sediments; on water and P, K, Ca, Mg in the water; and on the value of triple superphosphate, potassium chloride, urea, and limestone by water erosion were subjected to analysis of variance; when the averages differed, they were compared by the Duncan test (p≤0.05) through the statistical program ASSISTAT 7.7 Beta (Silva and Azevedo, 2016). A completely randomized experimental design was used, with two replications per treatment.

RESULTS AND DISCUSSION

Phosphorus, K, organic C, Ca, and Mg contents in the soil and sediments and water from erosion

The P, K, and organic C contents in the 0-0.025 m layer of the soil were higher in the treatments with crops (CT, MT and NT) than in the one without crops (BS) (Table 1). There was a significant variation between treatments (p≤0.01) in various combinations tested in both yearly seasons (summer and winter). This means that the soil management system influenced the P, K, and organic C contents in the topsoil in mean values over 15 years of study, agreeing with Andrade et al. (2012), who found the same tendencies for shorter periods of time. In the topsoil, there was no difference between the 2 yearly seasons, with the exception of P in NT and K in CT, in which the contents were higher in the autumn/winter. In the sediments from erosion, there was no difference. This means that the time of year did not really affect the nutrient and organic C contents on the soil surface and did not influence the sediments from erosion.

In the runoff water, the P and K contents were numerically lower than the contents in the soil and in the sediments from erosion (statistical analysis was not applied). In the case of P, the contents were higher than those normally present in natural sources of surface water, as verified by Shigaki et al. (2007) and Coletti et al. (2010). Among the treatments, there were significant differences (p≤0.01) in P and K contents in the runoff water in the spring/summer, but there were no differences in K content in the runoff water in the autumn/winter or in P content in the autumn/winter between MT and NT. The runoff water in the MT and NT treatments in spring/summer showed P content 4.2 times higher than in MT and NT (p≤0.05) in autumn/winter, on average. The P content in runoff waterin NT was 4.4 times higher than in CT in the autumn/winter. From these results, it appears that the P and K contents in runoff water are less influenced by variations in soil management and the season than the contents in the soil and in the sediments from erosion, as was also reported by Cassol et al. (2002).

The P contents in the topsoil were 4.4 times higher in NT than in CT, while the K contents were 1.8 times higher and the organic C contents 1.6 times higher, on average for the year (Table 1). The absence of tillage in NT, which allowed crop residue to remain on the soil surface, and the application of fertilizers on the surface without incorporation provided conditions for accumulation of these elements and organic C in the topsoil. This especially occurred with P because it is less mobile in the soil than K and organic C, as confirmed by Eltz et al. (1989), Pote et al. (1996), and Andrade et al. (2012). The P, K, and organic C contents in the CT treatment showed values closer to those of BS than to the values of MT; the values of the contents in MT came closer to NT. This can be explained by the fact that MT is similar to NT in terms of soil management, especially as regards the maintenance of crop residues on the surface. Therefore, MT is considered a conservationist soil tillage system, like NT.

The absence of crops, soil tillage twice a year, and maintaining the soil always uncovered for 15 years, contributed to reducing the contents of P, K and organic C in BS respectively 86, 74 and 42 % in relation to the average of the CT, MT and NT treatments (Table 1). Thus, the six

Table 1. Contents of extractable phosphorus, exchangeable potassium, and organic carbon (OC) in the 0-0.025 m layer of the soil in the sediments and water of erosion under natural rainfall, in a Humic Cambisol under different systems of use, management, and tillage of the soil (average of 15 years)

Treatment	C_1	C_2	$C_1 \times C_2$	C_1	C_2	$C_1 \times C_2$	C_1	C_2	$C_1 \times C_2$
	P			K			OC		
	—— mg dm^{-3} ——			—— mg dm^{-3} ——			—— g kg^{-1} ——		
0-0.025 m soil layer									
BS	10.1	6.9	ns	109	101	ns	21.8	18,9	ns
CT	25.9	19.2	ns	295	212	*	29.0	26,7	ns
MT	67.4	57.4	ns	539	460	ns	34.4	31,1	ns
NT	109.1	89.6	*	485	432	ns	47.6	41,7	ns
Contrast									
BS × (CT, MT, NT)	**	**		**	**		**	**	
CT × (MT, NT)	**	**		**	**		**	**	
MT × NT	**	**		**	**		**	**	
In eroded sediments									
BS	13.5	10.1	ns	108	90	ns	24.5	19,6	ns
CT	37.4	33.2	ns	227	249	ns	34.7	31,1	ns
MT	64.2	67.3	ns	362	386	ns	38.4	39,6	ns
NT	125.1	121.6	ns	504	561	ns	50.0	53,4	ns
Contrast									
BS × (CT, MT, NT)	**	**		**	**		**	**	
CT × (MT, NT)	**	**		**	**		**	**	
MT × NT	**	**		**	**		**	**	
In erosion water (mg L^{-1})									
BS	0.095	0.076	ns	2.45	2.84	ns			
CT	0.238	0.240	ns	3.91	6.07	ns			
MT	0.347	0.681	ns	4.55	8.92	**			
NT	1.056	1.553	*	8.18	19.68	**			
Contrast									
BS × (CT, MT, NT)	*	**		ns	**				
CT × (MT, NT)	*	**		ns	**				
MT × NT	ns	**		ns	**				

BS: bare soil without a crop; CT: conventional tillage; MT: minimum tillage; NT: no-tillage; C_1: autumn/winter; C_2: spring/summer; ns: not significant by the F test; ** and *: significant at $p \leq 0.01$ and $p \leq 0.05$, respectively, by the F test.

cropsin rotation for 15 years led to the accumulation of nutrients and organic C in the treatments with crops, as also reported by Eltz et al. (1989), Pote et al. (1996), and Andrade et al. (2012).

The P contents in the 0-0.025 m layer of the soil ranged from 10.1 to 109.1 mg kg^{-1} in the autumn/winter and from 6.9 to 89.6 mg kg^{-1} in the spring/summer in the NT, MT, and CT treatments; the lowest values were in BS and the highest in NT (Table 1). Among these treatments and in the same soil layer, the K contents ranged from 109 to 485 mg kg^{-1} in autumn/winter and from 101 to 432 mg kg^{-1} in spring/summer, whereas the organic C contents ranged from 21.8 to 47.6 g kg^{-1} in autumn/winter and from 18.9 to 41.7 mg kg^{-1} in spring/summer. The P, K, and organic C contents in the surface layer of soil were not statistically different between the seasons, with the exception of P in NT and K in CT (p≤0.05). The lower soil temperature in the autumn/winter, associated with growing oats, turnips, and vetch at that time of the year, promoted accumulation of organic C on the surface more than in the spring/summer due to lower biological activity and the larger amount of vegetable matter. In addition, cultures of autumn/winter tend to recycle more P and K than those grown in the spring/summer, corn, beans and soy.

The P and organic C contents in the sediments from erosion tended to be higher than the contents in the surface layer of the soil in all treatments, while the K contents were higher only in NT (Table 1). Thus, the possible deposition sites of sediments derived from erosion in all treatments should have a tendency to be enriched in P and organic C in relation to the location of the source of erosion, while in K, enrichment should occur only with the sediments originating from erosion in NT. The enrichment ratio (ER) can be obtained by dividing the contents in the sediments by the soil contents presented in table 1. For P, the ER was 1.23, while fororganic C, it was 1.07, in the average of the seasons of the year and the treatments.The NT stood out as the treatment whose sediments would most enrich the locations outside of the origin of erosion, with an ER of 1.24 for P, of 1.16 for organic C, and of 1.16 for K. ER values similar to these for NT were found by Schick et al. (2000) and by Shigaki et al. (2007) in other management systems. Phosphorus enrichment, mainly in still water sources, caused by water erosion is a serious problem, due to algae growth stimulated by eutrophication caused by this element (Hart et al., 2004).

The P contents in the sediments from erosion were 3.5 times higher in the NT treatment than in the CT treatment, while the K contents were 2.2 times higher and the organic C contents were 57 % higher, on average,in the seasons of the year (Table 1).The pollutant potential of the environment due to sediments from erosion generated by NT is inferred by this means, in terms of the amount of the element present in each dm^3 of sediments, particularly P, as also observed by Sharpley et al. (2001), and Hart et al. (2004). Thus, it is possible to control such pollution through actions that reduce the content of the chemical species in the sediments, or through actions to reduce the amount of sediments lost, or through both actions.

In the runoff water, the P and K contents partially differed among treatments and, in some cases, between the seasons (Table 1). The values of P and K ranged from 0.076 to 1.553 mg L^{-1} and from 2.45 to 19.68 mg L^{-1}, respectively, between treatments and seasons. In NT, the P contents in runoff water were 3.5 times higher than in CT on average in the seasons, while those of K were 3.2 times higher only in the spring/summer. These results are similar to those obtained by Schick et al. (2000). Significant variations, when they occurred, were expected, due to the combined effects of climate and the crop cycles for the same treatment, and of the soil management practices for the same crop. Therefore, the conservationist character of NT was partially compromised, since this soil management system was not as effective in controlling the loss of water and nutrients as it was in controlling soil loss, as reported by other authors (Schick et al., 2000; Sharpley et al., 2001; Bertol et al., 2014).

The Ca and Mg contents (Table 2) were consistent with the fact that the soil was corrected with limestone in the CT, MT, and NT treatments and kept without limestone in BS in the

soil surface layer, and this was reflected in the sediments and runoff water. In the surface layer, the contents of the two elements varied significantly between treatments for the two seasons. The exception was Mg in CT compared to the other two treatments under cropping. Moreover, there was significant variation between the seasons for all treatments. In the sediments from erosion, there was statistical variation among treatments and between seasons. The exceptions were CT, which did not differ from MT×NT, and MT, which did not differ from NT for Mg in the autumn/winter, as well as the lack of difference in Ca between the seasons for BS and NT and in Mg, also between seasons, for BS and CT. In the runoff water, the only significant differences were BS compared to the other treatments and MT, which differed from NT for both elements and seasons. We can thus observe the high sensitivity of Ca and Mg to the effects of soil management, climate, and type of crop in the surface layer of the soil and in the sediments from erosion.

On the soil surface, the Ca content in NT was 1.27 times the content in CT and the Mg content amounted to 1.31 times, while in the sediments from erosion, the contents were 1.40 and 1.39 times greater for Ca and Mg, respectively, in NT on average in the seasons

Table 2. Exchangeable calcium and magnesium contents in the 0-0.025 m layer of the soil, in the sediments and water from erosion under natural rainfall, in a Humic Cambisol, under different systems of land use and soil management (average of 15 years)

Treatment	C_1	C_2	$C_1 \times C_2$	C_1	C_2	$C_1 \times C_2$
	Ca			Mg		
	—— cmol$_c$ dm^{-3} ——			—— cmol$_c$ dm^{-3} ——		
0-0.025 m soil layer						
BS	4.4	5.8	**	1.7	2.9	*
CT	5.3	6.9	**	2.4	3.5	*
MT	5.8	7.8	**	2.7	4.0	*
NT	6.6	8.9	**	3.1	4.6	**
Contrast						
BS × (CT, MT, NT)	**	**		**	**	
CT × (MT, NT)	*	**		ns	ns	
MT × NT	**	**		*	*	
In eroded sediments						
BS	5.0	4.5	ns	2.4	2.8	ns
CT	5.7	5.0	*	2.6	3.1	ns
MT	6.5	5.5	**	3.0	3.7	**
NT	7.8	7.2	ns	3.3	4.6	*
Contrast						
BS × (CT, MT, NT)	**	**		*	**	
CT × (MT, NT)	**	**		ns	*	
MT × NT	**	**		ns	*	
In erosion water (mg L^{-1})						
BS	3.6	3.3	ns	2.2	1.9	ns
CT	6.2	5.1	ns	3.0	2.7	ns
MT	5.7	5.2	ns	3.0	3.2	ns
NT	4.9	5.3	ns	2.5	3.4	ns
Contrast						
BS × (CT, MT, NT)	**	*		**	*	
CT × (MT, NT)	ns	ns		ns	ns	
MT × NT	**	*		**	*	

BS: bare soil without a crop; CT: conventional tillage; MT: minimum tillage; NT: no-tillage; C_1: autumn/winter; C_2: spring/summer; ns: not significant by the F test; ** and *: significant at $p \leq 0.01$ and $p \leq 0.05$, respectively, by the F test.

of the year (Table 2). Thus, in the soil of NT, there was 27 and 31 % greater accumulation of Ca and Mg, respectively, than in CT on the soil surface. This is explained by the lack of soil tillage in NT, which allowed nutrients to accumulate on the surface layer, unlike what happened to CT, in which the nutrients were mixed into the soil layer by means of plowing and harrowing operations. From this accumulation, loss by erosion was 40 % greater for Ca and 39 % greater for Mg, which were adsorbed into the sediments, upon comparing the two soil management systems in question. This confirms that, in effect, NT is not fully a soil conservation system. The sediments resulting from the erosion of this management system are richer in chemical species than CT, as verified by Bertol et al. (2007a), Barbosa et al. (2009), and Dantas and Monteiro (2010). In the topsoil, the ratio between the contents of Ca and Mg was 2:1, whereas in the sediments from erosion, that ratio was 1.9:1 on average in the treatments and seasons. These ratios between Ca and Mg in the soil meet the minimum conditions required from the nutritional point of view for most plants grown.

Total losses of P, K, Ca, Mg, and organic matter (OM) and the cost of erosion

The total annual losses of P, K, Ca, Mg, and organic matter (OM) from erosion in runoff in general followed the combined effects of the contents in runoff (Tables 1 and 2) and of the total losses of sediments and water (Table 3). Regarding control of total losses of P in the sediments, the NT treatment was less effective than the CT and MT treatments, losses in NT were 23 and 26% higher than in the CT and MT treatments, respectively, differing from Dantas and Monteiro (2010). As for the total loss of K, Ca, and OM in the sediments, there was no significant difference among these treatments, only a tendency toward greater effectiveness in controlling these losses in NT compared to the other treatments with crops. For Mg, NT and MT were more effective than CT, unlike the results observed by other authors (Guadagnin et al., 2005). Thus, even if CT has lost 2.8 times more sediments than NT, the latter has lost more P in the sediments transported by water through erosion than the former. This demonstrates that due to the way the soil is being managed in NT, the system is not fully soil conservationist from the perspective of its ability to control losses of P, compared to CT.

In the case of runoff water, CT was more effective than NT in control of total losses of P and K, and less effective in control of losses of Ca and Mg (Table 3). The efficacy of CT in controlling total losses of P was 76 % compared to NT, while for the losses of K it was of 53 %, despite the total loss of water being 33 % higher in CT. This was explained mainly by the efficiency of 82 % of the CT in the control of the content of P and of 64 % in the control of the content of K in the water of flow (Table 1). As discussed in the case of P and K total losses in the sediments, NT is not fully a soil conservation treatment from the point of view of its ability to control the losses of P and K by water erosion compared to CT, due to low control of the water losses by NT (Bertol et al., 2007a; Bertol et al., 2015).

Comparing the NT and CT treatments, the total losses of P in the NT sediments amounted to 1.23 times those of CT; for K they amounted to 0.78; for Ca 0.50; for Mg 0.48; and for OM 0.55. Thus, NT allowed 23 % higher P losses than CT, whereas for K, the effectiveness

Table 3. Total annual losses of sediments and water, of extractable phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg), of exchangeable organic matter (OM) in the sediments, and of P, K, Ca, and Mg soluble in water from water erosion, under natural rainfall in the different treatments (Treat) in a Humic Cambisol (average of 15 years)

Treat	Sediment	P	K	Ca	Mg	OM	Water	P	K	Ca	Mg
	Mg ha^{-1} yr^{-1}	g ha^{-1} yr^{-1}	—————	kg ha^{-1} yr^{-1}	—————		m^3 ha^{-1} yr^{-1}	—————	g ha^{-1} yr^{-1}	—————	
BS	85.3 a	1,006 a	8.4 a	80.2 a	26.7 a	3,241 a	39.6 a	3.5 d	105 d	137 c	80 ab
CT	9.6 b	339 c	2.3 b	10.2 b	3.3 b	545 b	31.8 b	7.6 c	159 c	179 a	90 a
MT	5.0 c	330 c	1.9 b	6.0 b	2.4 c	335 b	27.8 bc	14.4 b	187 b	151 b	86 a
NT	3.4 c	416 b	1.8 b	5.0 b	1.6 c	300 b	24.0 c	31.3 a	335 a	123 d	73 b
CV (%)	7.9	4.1	9.0	14.1	3.5	8.9	4.9	6.6	2.2	3.0	4.9

BS: bare soil without a crop; CT: conventional tillage; MT: minimum tillage; NT: no-tillage; CV: coefficient of variation; p≤0.01, with the exception of magnesium in the water, where p≤0.05 by the Duncan test.

of NT was a 22 % reduction in loss compared to CT, and for the other nutrients and OM, the effectiveness of NT was approximately a 50 % reduction in loss, considering only the sediments. Therefore, specifically in regard to losses of P through the sediments, NT was actually not an entirely conservationist soil management system, a problem already identified by Bertol et al. (2007a) and Bertol et al. (2014). Taking into account that P is potentially the element causing eutrophication of surface waters, the likely place of deposition of fine sediments carried by water erosion (Shigaki et al., 2007), this is a serious problem. Moreover, it is important to consider that losses of P, other elements, and OM by water erosion are responsible for soil depletion and increased cost of agricultural production (Dantas and Monteiro, 2010; Dechen et al., 2015).

In the runoff water, the overall losses of P, K, Ca, and Mg (Table 3) generally followed the tendency of the contents of these elements in water (Tables 1 and 2). In the case of P, total losses were 4.1 times greater in NT than in CT, whereas for K, the difference was 2.1 times. This confirms that NT is not fully soil conservationist with respect to control of total losses of these two elements through erosion. This once more highlights the problem of P losses by erosion in relation to potential pollution of surface watersby this element due to eutrophication, as already noted by Hart et al. (2004).

The total annual loss of P by water erosion in the NT system may seem small considering the absolute amount, 416 g ha^{-1} adsorbed to sediments and 31.3 g ha^{-1} soluble in water (Table 3), for a total of 447.3 g ha^{-1}. However, depending on the volume of water in the body of water where this material from erosion will be deposited, the environmental damage may be significant, especially considering that these losses are added together temporally. Furthermore, one must consider two important aspects when analyzing these numbers. First, these losses were quantified experimentally, on a plot scale, with only 22.1 m slope length, and, secondly, they were quantified under management conditions with relatively small amounts of fertilizer applied annually in the soil compared to the amounts that farmers generally apply on crops. On a field scale, the slope length and water volume and speed are greater and, therefore, with more capacity for shearing and transporting sediments than on the plot scale in erosion experiments (Bagarello et al., 2011; Bagarello et al., 2013). In agricultural areas managed under NT conditions, amounts of fertilizer greater than in the experiments generate increased contents of P on the soil surface, available for transport. The result is that the values of P lost through water erosion in experimental areas underestimate the values of P lost in crop areas and, in this case, the environmental problems related to eutrophication of waters by P are greater.

The cost of losses of P, K, and N represented by the fertilizers triple superphosphate, K chloride, and urea, and of Ca and Mg represented by limestone, varied among the CT, MT, and NT treatments (Table 4). The NT treatment was more effective in reducing the total cost of these losses, which were 45% lower than in CT, the effectiveness of which was more pronounced in cost reduction regarding losses of urea (65%) and limestone (50%). In the case of triple superphosphate (P) alone, the cost of losses was 29% higher in NT than in CT, but without a significant difference. Based on these data, we can infer that soil management

Table 4. Value of triple superphosphate fertilizer (TSF - phosphorus), potassium chloride (KCl - potassium), and urea (nitrogen in the organic matter) and of limestone (Ca + Mg) lost annually in the sediments and water from erosion under natural rainfall, in the different treatments (Treat) in a Humic Cambisol (average of 15 years)

Treat	TSF	KCl	Urea	Limestone	Total
			US$ ha^{-1} yr^{-1}		
BS	2.92 a	7.60 a	59.68 a	22.40 a	92.60 a
CT	0.99 c	2.18 b	6.73 b	2.88 b	12.78 b
MT	0.99 c	1.83 b	3.49 c	1.73 c	8.04 c
NT	1.31 b	1.89 b	2.34 c	1.44 c	6.98 c
CV (%)	6.7	6.7	4.1	4.5	2.8

BS: bare soil without a crop; CT: conventional tillage; MT: minimum tillage; NT: no-tillage; CV: coefficient of variation. Values considered for calculating the cost of inputs on February 16, 2016: TSP: 0.538 US$ kg^{-1}; KCl: 0.442 US$ kg^{-1}; urea: 0.442 US$ kg^{-1}; limestone: 0.042 US$ kg^{-1}. (p≤0.01, Duncan).

by NT may represent significant savings in the cost of the farming compared to CT in regard to fertilizers and limestone (Dantas and Monteiro, 2010). Nevertheless, however small they may be, all losses should be considered in the overall cost of agricultural activity.

Ratios between the values of the P, K, and organic C contents in the sediments and in the soil, and the enrichment rate

The linear regression model, y = a + bx, fit the data of P, K, and organic C in the ratio between the contents in the sediments from erosion and the contents in the soil on the surface layer, for the seasonal as well as the annual data (Figures 1 and 2).
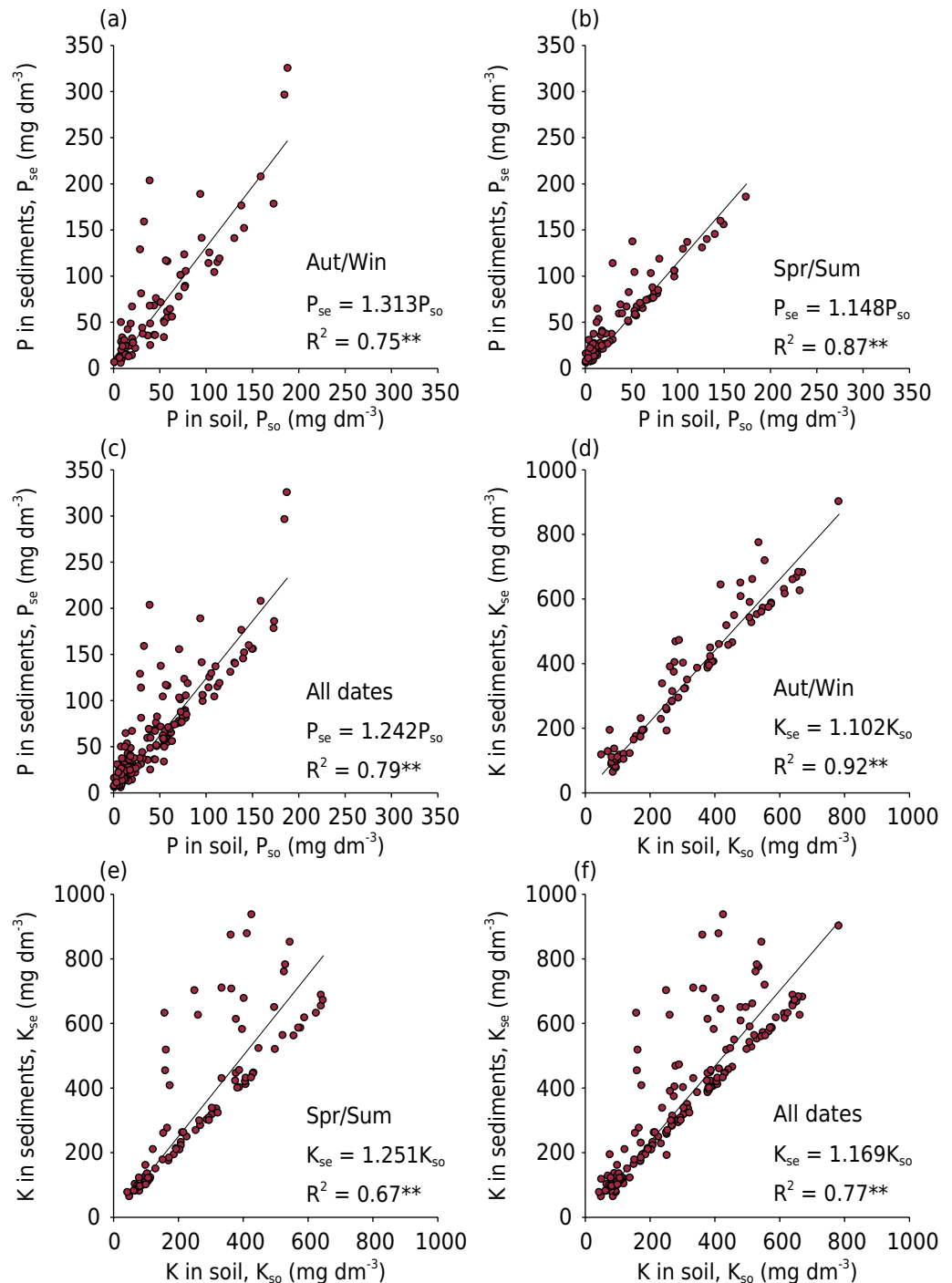
Figure 1. Relationship between extractable phosphorus contents (a), (b), and (c) and exchangeable potassium (d), (e), and (f) in eroded sediments and in the soil layer from 0 to 0.025 m, in a Humic Cambisol for 15 years under natural rainfall conditions. P_{se}: phosphorus in the sediments; P_{so}: phosphorus in the soil; K_{se}: potassium in the sediments; K_{so}: potassium in the soil; Aut/Win: autumn/winter; Spr/Sum: spring/summer.
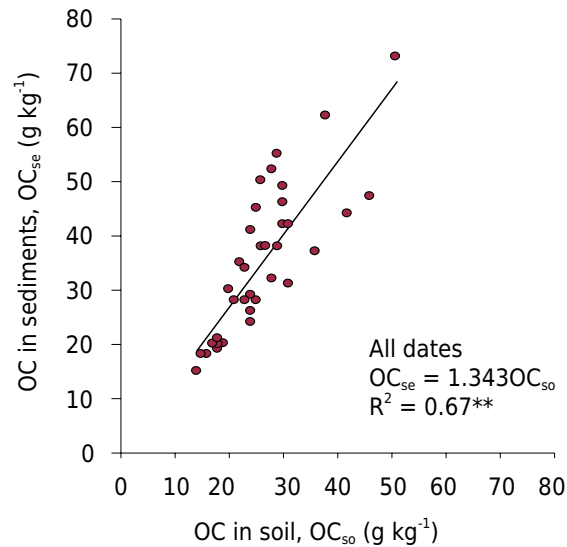
Figure 2. Relationship between total organic carbon (OC) contents in eroded sediments and in the 0-0.025 m layer of the soil, in a Humic Cambisol for 15 years under natural rainfall conditions. OC_{so}: organic carbon in the soil; OC_{se}: organic carbon in the sediments.

The regression coefficient for P was 1.313 for the autumn/winter data (Figure 1a), 1.148 for the spring/summer data (Figure 1b), and 1.242 considering the annual data (Figure 1c). For K, the values of the coefficient were 1.102 for the autumn/winter data (Figure 1d), 1.251 for the spring/summer data (Figure 1e), and 1.169 for the annual data (Figure 1f). In the case of organic C, the value of the annual data regression coefficient was 1.343 (Figure 2). The regression coefficient values in figures 1 and 2 also mean ER for P, K, and organic C, since they are >1. These values are similar to the ER obtained by the quotient between the contents in the sediments and in the soil, as already discussed above. Thus, on average annually, the enrichment of the erosion disposition sites was 24.2 % for P, 16.9 % for K, and 34.3 % for organic C. Values of ER >1 for P, K, and organic C were also verified by Schick et al. (2000).

Water erosion is an important form of environmental enrichment with chemical species outside the sites of origin of erosion, due to the selectivity of the erosion. The more soil conservationist tillage system is, the more pronounced the selectivity of erosion, because in such systems, these sediments carried by the runoff are mostly colloidal, with higher capacity for adsorption of chemical species than non-colloidal sediments, as demonstrated by Lewis and Wurtsbaugh (2008) and Barbosa et al. (2009). Thus, NT, for example, presents a potential pollutant of the environment, considering the ratio between the contents of chemical species existing in the soil and the content existing in the sediments and water of erosion. Therefore, it is important to recommend conservation practices to control runoff in NT in order to complement the action of soil cover by crop residues for control of water erosion.

CONCLUSIONS

The linear model, $y = a + bx$, fits the data within the level of significance ($p \leq 0.01$) when we compare the phosphorus, potassium, and organic carbon contents in the sediments from soil erosion with the contents in the 0-0.025 m layer, both seasonally and annually.

Organic C and nutrient contents are greater in the sediments from erosion than in the soil where erosion a rose, resulting in enrichment ratios >1 for P, K, and organic C.

The hypothesis that the concentration of nutrients and organic C in the runoff derived from no-tillage are greater than those of conventional tillage, in the sediments as well as in the water, was also confirmed.

The cost of the total losses of nutrients in the form of triple superphosphate fertilizer, K chloride, and urea and limestone by water erosion was higher in conventional tillage than in no-tillage, indicating efficacy of 45 % in no-tillage in reducing this value compared to conventional tillage. In the specific case of triple superphosphate, the cost of erosion losses is 29 % higher in no-tillage than in conventional tillage, while in urea and limestone, the effectiveness of no-tillage in controlling costs is 65 and 50 %, respectively.

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