

# Losses and costs associated with water erosion according to soil cover rate

Sonia Carmela Falci Dechen <sup>(1)</sup>; Tiago Santos Telles <sup>(2\*)</sup>; Maria de Fátima Guimarães <sup>(3)</sup>; Isabella Clerice De Maria <sup>(1)</sup>

<sup>(1)</sup> Instituto Agronômico (IAC), Centro de Pesquisa e Desenvolvimento de Solos e Recursos Ambientais, Av. Barão de Itapura, 1.481, 13020-902 Campinas (SP), Brasil.

<sup>(2)</sup> Instituto Agronômico do Paraná (IAPAR), Área de Socioeconomia, Rodovia Celso Garcia Cid km 375, 86047-902 Londrina (PR), Brasil

<sup>(3)</sup> Universidade Estadual de Londrina (UEL), Departamento de Agronomia, Rodovia Celso Garcia Cid PR 445 km 380 s/n, 86057-970 Londrina (PR), Brasil.

(\* Corresponding author: [telles@iapar.br](mailto:telles@iapar.br)

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## Abstract

The aim of this study was to estimate water erosion costs associated with nutrient losses in four different rates of artificial cover. The experiment was carried out from 1987 to 1996 in runoff plots to measure soil losses in Campinas, State of Sao Paulo, in an Ferralsol under natural rainfall. The experimental design was completely randomized, with four treatments (0%, 24%, 40% and 90% artificial cover) and three replications. To estimate costs, P, K<sup>+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup> concentrations in runoff water and soil removed by erosion were summed up, converted into triple superphosphate, potassium chloride and dolomitic limestone and multiplied by their respective market prices. The results indicate that, under the experimental conditions, the greater the percentage of soil cover, the lower the losses of water, soil, organic matter and nutrients. The soil with 90% cover presented reduction of 51.97% in average water losses, 54.44 in soil losses and 54.91% in organic matter losses than the treatment with 0% cover. In bare soil, losses were estimated at 16% P<sub>2</sub>O<sub>5</sub> and 8% KCl in terms of the amount of fertilizers recommended. Costs varied from US\$ 107.76 ha<sup>-1</sup> year<sup>-1</sup> in bare soil (0% cover) to US\$ 18.15 ha<sup>-1</sup> year<sup>-1</sup> in soil with 90% cover. With these values, losses were estimated at 616.5 million tons of soil per year for Brazil, as a result of soil erosion in annual crops, and cost of this process is around US\$ 1.3 billion per year.

**Key words:** soil losses, water losses, nutrient losses, economic valuation, environmental valuation.

## 1. INTRODUCTION

Water erosion is one of the main forms of degradation of agricultural land in Brazil. It is a process of overland flow by runoff water, in which there is detachment, transport and deposition of soil particles, nutrients and organic matter (OM). The occurrence of erosion is determined, inter alia, by factors such as rainfall erosivity, soil erodibility and vegetation cover, and the soil cover is a major factor in controlling water erosion.

The main consequences of erosion are losses of water, soil, OM, nutrients and the costs generated (Pimentel et al., 1995; Telles et al., 2011; Telles et al., 2013a). The study of this phenomenon is of utmost importance, since freshwater is a scarce natural resource and that the gradual losses of soil can turn it into an unproductive land (Pimentel et al., 1995; Lal, 1998; Den Biggelaar et al., 2003a, b). In addition, spending on fertilizers, which represent between 20% and 41% of production costs in crops such as soybeans, corn

and wheat (Matson et al., 1998; Castro et al., 2006; Cavalett & Ortega, 2009; Souza et al., 2012), and the volume of inputs applied to a crop which can be washed out by rainwater, can pose significant economic losses with a substantial impact on costs and revenue of farmers. Besides that, there are costs of repairing damage caused by erosion in farms, such as working hours and machinery for replanting crops and maintenance of terraces.

The use of crop residues for ground cover is a simple and effective way to control erosion in planted areas (Meyer et al., 1970; Bertol et al., 1997; Morais & Cogo, 2001; Bertol et al., 2007). This residue is able to dissipate the erosive energy of raindrops, minimizing the detachment and surface sealing of the soil, contributing to increase water infiltration into the soil. These factors help support the hypothesis that the soil cover reduces losses of water, land, OM, nutrients and costs. Several

studies have demonstrated the efficacy of conservation tillage associated with the use of crop residues on the soil in erosion control. These practices enable reductions of 50% to 100% in soil losses compared to conventional tillage – PC (Bertol et al., 1997; Bertol et al., 2007; Morais & Cogo, 2001). Among the most investigated conservation tillage practices, soil losses in no-tillage (PD), in general, is lower than in PC and in minimum tillage systems - PM - (Eltz et al., 1984a, b; Bertol et al., 2007; Pugliesi et al., 2011), given the higher percentage of soil cover and slighter disturbance of the soil. Systems with soil cover indices over 30% during cultivation and fallow periods are considered conservation systems (Lopes et al., 1987; Machado & Silva, 2001; Soane et al., 2012).

In Brazil, the association of physical losses caused by erosion with their economic aspects is not new (Telles et al., 2013b), but this approach was considered in a few studies (Marques et al., 1961; Sorrenson & Montoya, 1989; Martin et al., 1991; Marques, 1998; Rodrigues, 2005; Bertol et al., 2007; Sarcinelli et al., 2009; Dantas & Monteiro, 2010; Pugliesi et al., 2011; Andrade et al., 2011). Although these have addressed only the losses of nutrients in the production unit (on-site), representing a small portion of the total costs of soil erosion (Crosson, 1995), this information is important for farmers, researchers and

policy makers to form their opinions on the conservation management practices.

In this context, this study evaluated losses of water, soil, OM and nutrients, and estimated the costs of erosion according to four soil cover rates.

## 2. MATERIAL AND METHODS

### Study area

The experiment was conducted between 1987 and 1996, in the Experimental Center of the Agronomic Institute (IAC), Campinas, São Paulo State, Brazil (22°51'S and 47°4'W; 630 m altitude) figure 1, in a Ferralsol (classified according to Santos et al., 2006). According to the Köppen classification, the climate is Cwa, tropical of altitude, with dry winter and wet and hot summer. The average annual rainfall is 1,430 mm. The average temperature is 20.5°C (Setzer, 1966). The average annual erosivity is 6,738 mm ha<sup>-1</sup> h<sup>-1</sup>year<sup>-1</sup>, with 62% of the annual erosion potential occurring from December to February (Lombardi & Moldenhauer, 1992). The history of the experimental area is described in Marques (1951), Marques et al. (1961) and Tengberg et al. (1997).

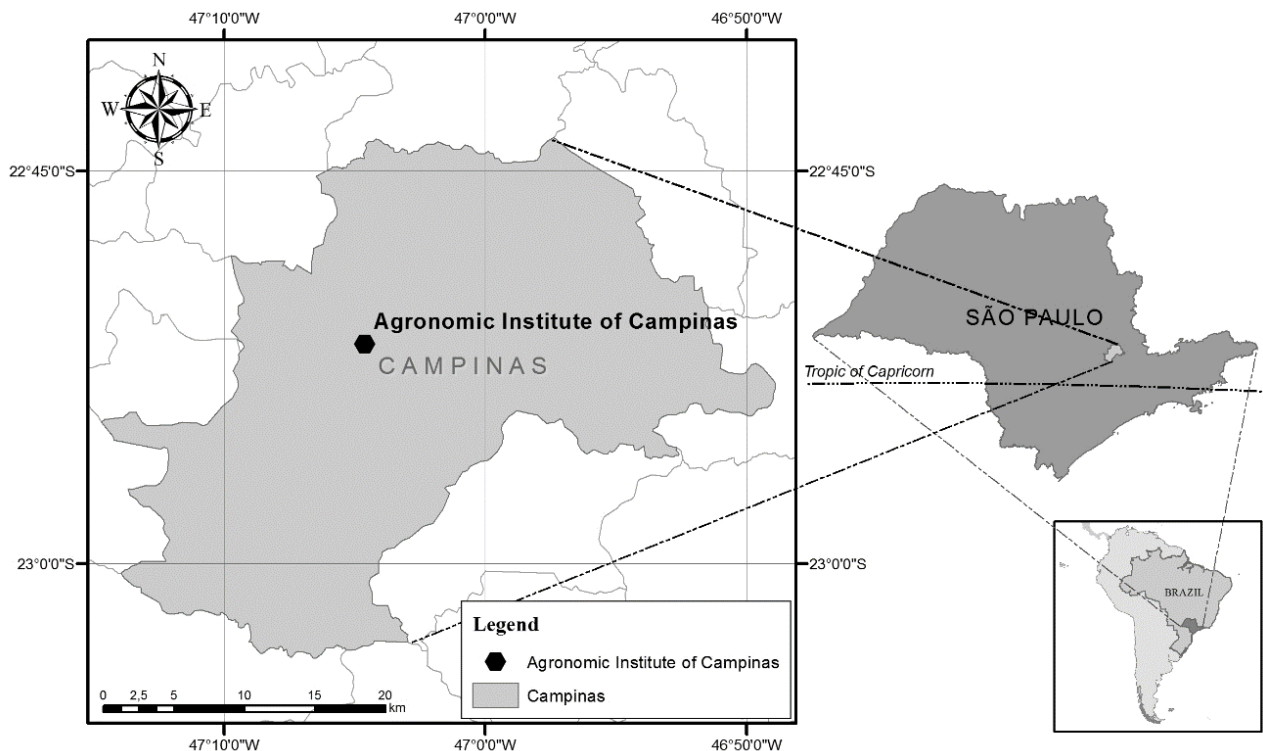


Figure 1. Location of the study area.

**Table 1.** Physical and chemical soil properties, in August 1987, before the start of the experiment, at the 0-0.20 m layer

Sand	Silt	Clay	pH	OM	P	Ca <sup>2+</sup>	Mg <sup>2+</sup>	K <sup>+</sup>	CEC	V
	(%)		(CaCl <sub>2</sub> )	(g dm <sup>-3</sup> )	(mg dm <sup>-3</sup> )		(mmol dm <sup>-3</sup> )			(%)
34	9	57	5.3	37	7.5	38	16	2.5	89	65

OM: organic matter. EC: cation exchange capacity. V: base saturation.

## Evaluation of losses of soil, water and nutrients

The experimental design was completely randomized with four treatments and three replications. The treatments consisted of four soil cover rates: 0%, 24%, 40% and 90%. The treatment 0% coverage was kept fully bare. In the treatment with 24% cover, 2/5 of the plot was kept bare and 3/5 covered with 18% shading screen. In the other two treatments, 40% and 90% cover, we used 18% and 30% shading screens in the entire plot. The values of 40% and 90% are close to the values considered as soil cover with crop residues for conservation management and no-tillage system (SPD), respectively (Cline & Hendershot, 2006). The soil was kept without vegetation, manually weeded, so that the growth of weeds under the shading screen did not alter the coverage condition. In the year before the experiment onset, all plots were planted with sunnhep (*Crotalaria juncea* L.) without fertilizers. The draw of the treatments in the plots considered the history of the area, which consisted of cultivation of annual plants with and without crop rotation, so that the repetitions were distributed among the various previous uses. The experimental area received no fertilizer in the study period.

The plots were 100 m<sup>2</sup>, 25 m long and 4 m wide, with an average slope of 9%. The runoff collection system consists of two concrete tanks, separated by a Geib divider, in which 1/7 of the runoff is collected.

Table 1 shows the mean values of some physical and chemical soil properties, at the 0-0.20 m layer, in August 1987, before the start of the experiment. The analyses were performed on soil samples made up of three subsamples, using the procedures described by Quaggio & van Raij (1979) and van Raij et al. (2001) for chemical attributes and Camargo et al. (2009) for the texture fractions.

After each rainfall event, this study considered only rainfall with 40 mm or more, the storage tanks were drained to quantify losses of water and soil, following the procedure described by Bertoni (1949). Samples of soil transported by erosion were collected to determine the content of organic matter (OM), P, K<sup>+</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>, Cu<sup>2+</sup>, Fe<sup>3+</sup>, Mn<sup>2+</sup> and Zn<sup>2+</sup>; and samples of runoff water were taken to determine the concentrations of P, K<sup>+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup>. The OM content was determined by colorimetric method (Quaggio & van Raij, 1979). The concentrations of P, K<sup>+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup> were

determined with ion exchange resin; the concentration of P by the colorimetric method, K<sup>+</sup>, by flame photometry, and Ca<sup>2+</sup> and Mg<sup>2+</sup>, by atomic absorption spectrophotometry (van Raij et al., 2001). Concentrations of Cu<sup>2+</sup>, Fe<sup>3+</sup>, Mn<sup>2+</sup> e Zn<sup>2+</sup> were determined by ICP-OES after extraction by the DTPA method, at pH 7.3.

## Estimating soil erosion costs

To estimate the costs of nutrient losses, based on the losses of P, K<sup>+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup>, their concentrations in the runoff water and soil transported by erosion were summed up and converted into commercial fertilizers. P was expressed as triple superphosphate (P<sub>2</sub>O<sub>5</sub>, 42%), K<sup>+</sup> as potassium chloride (KCl, 60%) and Ca<sup>2+</sup> and Mg<sup>2+</sup> as dolomitic limestone [CaMg(CO<sub>3</sub>)<sub>2</sub>, 38%].

Prices paid by farmers for these fertilizers were obtained from the Institute of Agricultural Economics (IEA) in the State of São Paulo and the Department of Rural Economy (Deral), Secretariat of Agriculture and Supply of the Parana State. For calculation, we considered the prices in real currency paid in March 2011, converted into US dollars<sup>(4)</sup>. The assumed value for the ton of triple superphosphate was US\$ 682.84, for the potassium chloride, US\$ 929.49, and for the dolomitic limestone, US\$ 40.98.

The costs estimate was based on equation 1 (Telles et al., 2013b):

$$C = \sum_{i=1}^m (Q_i P_i) \quad (1)$$

where: C is the soil erosion costs related to losses of the analyzed nutrients (P, K<sup>+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup>); Q<sub>i</sub> is the amount of fertilizer lost by erosion; P<sub>i</sub> the price per ton of different fertilizers; and m is the different fertilizers (in this case, triple superphosphate, potassium chloride and dolomitic limestone).

## Statistical analysis

Annual data of losses of water, soil and nutrients and costs estimates on the basis of soil cover rates were subjected to analysis of variance and regression at 1% (p≤0.01) and 5% (p≤0.05) levels. Analyses were run with the Statistical Analysis System 9.3 (SAS<sup>®</sup>).

<sup>(4)</sup>Exchange Rate on March 3rd, 2011.

### 3. RESULTS

#### Losses of soil, water and organic matter

The average annual loss of water, soil and OM caused by erosion between 1987 and 1996 showed a significant reduction according to the soil cover rates (0%, 24%, 40% and 90%), following a second order polynomial model (Table 2). Comparing the treatments with 0% and 90% cover, reductions were found in losses of water (51.97%), soil (54.44%) and OM (54.91%). Between the treatments with 0% and 40% cover, there was also a reduction in losses of water (8.36%), soil (8.23%) and OM (10.48%). Between the treatments with 0% and 24% cover, reductions in losses

of water, soil and OM were 3.08%, 8.95% and 11.38%, respectively.

#### Nutrient losses

In the runoff water, nutrient losses decreased linearly with increasing soil cover (Table 3). Comparing the bare soil (0% soil cover) with 90% cover, the latter showed lower losses of P (84.11%), K<sup>+</sup> (85.86%), Ca<sup>2+</sup> (91.97%) and Mg<sup>2+</sup> (89.64%). In the soil with 0% cover in relation to the soil with 40%, lower losses were found for P (65.42%), K<sup>+</sup> (73.79%), Ca<sup>2+</sup> (83.83%) and Mg<sup>2+</sup> (74.61%). In the soil with 0% cover compared to the soil with 24%, lower losses were observed for P (31.78%), K<sup>+</sup> (35.52%) and increased

**Table 2.** Annual averages of losses of water, soil and organic matter by water erosion between 1987 and 1996, according to four different rates of soil cover

Cover (%)	Water (mm year <sup>-1</sup> )	Soil (Mg ha <sup>-1</sup> year <sup>-1</sup> )	OM (kg ha <sup>-1</sup> year <sup>-1</sup> )
0	170.74	27.59	685.96
24	165.48	25.12	607.88
40	156.46	25.32	614.05
90	82.00	12.57	309.31
Regression	$y = 169.48 + 1.83x - 0.157x^2$	$y = 27.25 + 0.002x - 0.002x^2$	$y = 675.22 + 3.47x - 0.51x^2$
R <sup>2</sup>	0.70*	0.82*	0.84*

OM: organic matter. \* p ≤ 0.01.

**Table 3.** Annual averages of losses of P, K<sup>+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup> in the runoff water and soil transported by erosion between 1987 and 1996, according to four different rates of soil cover

Cover (%)	P	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>
(kg ha <sup>-1</sup> year <sup>-1</sup> )				
Runoff water				
0	1.07	2.90	9.46	1.93
24	0.73	1.87	1.67	1.26
40	0.37	0.76	1.53	0.49
90	0.17	0.41	0.76	0.20
Regression	$y = 1.04 - 0.031x$	$y = 1.00 - 0.019x$	$y = 9.23 - 0.786x - 0.017x^2$	$y = 1.83 - 0.060x$
R <sup>2</sup>	0.69**	0.58**	0.94*	0.53*
Soil transported by erosion				
0	0.77	0.98	12.99	3.81
24	0.75	0.81	11.56	3.71
40	0.63	0.70	10.77	3.31
90	0.38	0.42	5.50	1.64
Regression	$y = 0.83 - 0.013x$	$y = 1.00 - 0.019x$	$y = 12.89 + 0.012x - 0.009x^2$	$y = 3.72 + 0.05x - 0.004x^2$
R <sup>2</sup>	0.46**	0.46**	0.73*	0.77*
Total				
0	1.84	3.88	22.46	5.74
24	1.48	2.68	13.23	4.97
40	1.00	1.46	12.30	3.80
90	0.55	0.83	6.26	1.84
Regression	$y = 1.87 - 0.044x$	$y = 3.76 - 0.105x$	$y = 21.19 - 0.517x$	$y = 6.01 - 0.130x$
R <sup>2</sup>	0.72*	0.61**	0.82*	0.63*

\* p ≤ 0.01. \*\* p ≤ 0.05.

losses for  $\text{Ca}^{2+}$  (82.35%) and  $\text{Mg}^{2+}$  (34.72%). The total amounts of nutrients in runoff water were of the following order:  $\text{Ca}^{2+} > \text{K}^+ > \text{Mg}^{2+} > \text{P}$ . This same sequence was observed by Hernani et al. (1999) who evaluated nutrient losses in an Oxisol of Dourados, Mato Grosso do Sul State, and by Silva et al. (2005), evaluating nutrient losses in an Oxisol of Lavras, Minas Gerais State.

Regarding the losses of nutrients in eroded sediments (Table 3), the reduction in relation to increasing soil cover was linear for P and  $\text{K}^+$ , and polynomial for  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ . Comparing the bare soil with the soil with 90% cover, the latter resulted in lower losses of P (50.65%),  $\text{K}^+$  (57.14%),  $\text{Ca}^{2+}$  (57.66%) and  $\text{Mg}^{2+}$  (55.80%). In turn, in the comparison of the soil with 0% cover to the soil with 40% cover, lower losses were found in the latter for P (18.18%),  $\text{K}^+$  (28.57%),  $\text{Ca}^{2+}$  (17.09%) and  $\text{Mg}^{2+}$  (10.78%). When analyzing the soil with 0% compared with the soil with 24% cover, the latter also showed minor losses of P (2.60%),  $\text{K}^+$  (17.35%),  $\text{Ca}^{2+}$  (11.01%) and  $\text{Mg}^{2+}$  (2.62%). The tendency of nutrient losses in eroded sediments was as follows:  $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+ > \text{P}$ .

In the case of total losses of P,  $\text{K}^+$ ,  $\text{Ca}^{2+}$  e  $\text{Mg}^{2+}$ , in the comparison between the treatments 0% and 90%, the latter produced lower losses at 70.11%, 78.61%, 72.13% and 67.94%, respectively. Comparing the treatment 0% with 40%, losses of P,  $\text{K}^+$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  were, respectively, 45.65%, 62.37%, 45.24% and 33.80% lower. Finally, in the comparison of the treatment with 0% cover with the soil with 24% cover, losses of P,  $\text{K}^+$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  were 19.57%, 37.31%, 41.10% and 13.41%, respectively. The total losses of nutrients - the sum of the losses in runoff water and eroded sediments - followed the order:  $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+ > \text{P}$ .

In general, the average losses of  $\text{Cu}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Mn}^{2+}$  and  $\text{Zn}^{2+}$  in the soil transported by erosion were also reduced due to the soil cover (Table 4). Comparing the soil with 90% cover with that with 0% (bare soil), the first had lower losses of  $\text{Cu}^{2+}$  (50%),  $\text{Fe}^{3+}$  (54.16%) and  $\text{Mn}^{2+}$  (63.89%). In the treatment 40% cover, compared with the soil with 0% cover, there were also minor losses of  $\text{Cu}^{2+}$  (18.75%),  $\text{Fe}^{3+}$  (4.17%) and  $\text{Mn}^{2+}$  (30.99%), and higher of  $\text{Zn}^{2+}$  (50%). In the soil with 24% cover, compared to the soil with 0%,

lower losses were registered for  $\text{Cu}^{2+}$  (6.25%),  $\text{Fe}^{3+}$  (20.83%) and  $\text{Mn}^{2+}$  (8.95%), and higher for  $\text{Zn}^{2+}$  (50%).

The average losses and the total amounts of P, expressed as triple superphosphate ( $\text{P}_2\text{O}_5$ , 42%), of  $\text{K}^+$ , as potassium chloride (KCl, 60%) and of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , as dolomitic limestone [ $\text{CaMg}(\text{CO}_3)_2$ , 38%], were reduced according to the soil cover, for both the runoff water and the eroded sediments (Table 5).

Losses of  $\text{P}_2\text{O}_5$  were lower in runoff water than in eroded sediments. In the runoff water, in the soil with 90% cover, losses of that element was reduced by 83.03% compared with bare soil (0% cover). For the treatments of 40% and 24% cover, compared to the soil with 0%, losses were reduced by 64.08% and 27.98%, respectively. In the eroded sediments, these losses were reduced by 53.21%, 18.29% and 3.56% for the treatments 90%, 40% and 24% soil cover, respectively, compared with bare soil (0% cover).

With respect to KCl, lower losses were also found in runoff water than in eroded sediments. Compared to the soil with 0% cover, losses in runoff of water were 86.12%, 74.41% and 36.96% lower for the treatments of 24%, 40% and 90% cover, respectively. In the same comparison, the losses in the eroded sediments were 57.79%, 29.65% and 18.59%.

As for  $\text{CaMg}(\text{CO}_3)_2$ , losses followed the same trend, i.e. in the runoff water, compared to soil with 0% cover were, 86.38% lower in the soil with 90%, 71.02% in that with 40% cover, and 56.66% in that with 24%. In eroded sediments, following the same comparison, the differences were 56.95%, 14.98% and 7.02, respectively.

### On-site costs of soil erosion

Soil erosion costs associated with the loss of nutrients in the form of triple superphosphate ( $\text{P}_2\text{O}_5$ , 42%), potassium chloride (KCl, 60%) and dolomitic limestone [ $\text{CaMg}(\text{CO}_3)_2$ , 38%], in US\$  $\text{ha}^{-1} \text{year}^{-1}$ , decreased with increasing soil cover rates (Table 6).

The highest costs were observed in soil with 0% cover, amounting to US\$ 107.76 per  $\text{ha}^{-1} \text{year}^{-1}$  and showing a

**Table 4.** Annual averages of losses of  $\text{Cu}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Mn}^{2+}$  and  $\text{Zn}^{2+}$  in the soil transported by water erosion between 1987 and 1996, according to four different rates of soil cover

Cover (%)	$\text{Cu}^{2+}$	$\text{Fe}^{3+}$	$\text{Mn}^{2+}$	$\text{Zn}^{2+}$
			( $\text{kg ha}^{-1}\text{year}^{-1}$ )	
0	0.16	0.24	3.13	0.04
24	0.15	0.19	2.85	0.06
40	0.13	0.23	2.16	0.06
90	0.08	0.11	1.13	0.04
Regression	$y = 0.17 - 0.003x$	$y = 0.25 - 0.004x$	$y = 3.14 - 0.013x - 0.002x^2$	$y = 0.05 + 0.003x - 9.15 \cdot 10^{-5}x^2$
R <sup>2</sup>	0.72**	0.65**	0.63*	0.76**

\*  $p \leq 0.01$ . \*\*  $p \leq 0.05$ .



**Table 5.** Annual averages of losses of triple superphosphate ( $P_2O_5$ , 42%), potassium chloride (KCl, 60%) and dolomitic limestone [ $CaMg(CO_3)_2$ , 38%], in runoff water and eroded sediments, between 1987 and 1996, according to four different rates of soil cover

Cover (%)	$P_2O_5$	KCl ( $kg\ ha^{-1}year^{-1}$ )	$CaMg(CO_3)_2$
Runoff water			
0	5.54	5.98	26.88
24	3.99	3.77	11.65
40	1.99	1.53	7.79
90	0.94	0.83	3.66
Regression	$y = 54.72 - 1.597x$	$y = 56.55 - 1.781x$	$y = 236.49 - 7.562x$
R <sup>2</sup>	0.41**	0.35**	0.36**
Soil transported by erosion			
0	4.21	1.99	63.67
24	4.06	1.62	59.20
40	3.44	1.40	54.13
90	1.97	0.84	27.41
Regression	$y = 4.22 + 0.125x - 0.003x^2$	$y = 2.02 - 0.038x$	$y = 63.31 - 0.308x + 0.050x^2$
R <sup>2</sup>	0.53**	0.46**	0.76*
Total (runoff water + eroded sediments)			
0	9.74	7.96	90.55
24	8.06	5.39	70.85
40	5.43	2.93	61.93
90	2.91	1.67	31.07
Regression	$y = 59.26 - 1.673x$	$y = 58.57 - 1.819x$	$y = 305.21 - 8.757x$
R <sup>2</sup>	0.43**	0.36**	0.41**

\*  $p \leq 0.01$ . \*  $p \leq 0.05$ .**Table 6.** Annual averages of soil erosion costs associated with losses of P, K<sup>+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup>, expressed in the form of triple superphosphate ( $P_2O_5$ , 42%), potassium chloride (KCl, 60%) and dolomitic limestone [ $CaMg(CO_3)_2$ , 38%], in US\$  $ha^{-1}year^{-1}$ , between 1987 and 1996, according to four different rates of soil cover

Cover (%)	$P_2O_5$ (42%)	KCl (60%)	$CaMg(CO_3)_2$ (38%)	Total
(US\$ $ha^{-1}year^{-1}$ )				
0	40.68	57.39	9.69	107.76
24	30.05	36.50	5.12	71.67
40	15.96	15.57	3.85	35.38
90	7.76	8.53	1.86	18.15
Regression	$y = 40.47 - 1.143x$	$y = 54.44 - 1.691x$	$y = 8.89 - 0.255x$	$y = 95.44 - 0.966x$
R <sup>2</sup>	0.65**	0.60**	0.64**	0.62**

\*\*  $p \leq 0.05$ .

difference of US\$ 36.09, US\$ 72.38 and US\$ 89.61 per  $ha^{-1} year^{-1}$ , respectively, for the soils with 24%, 40% and 90% cover rates.

The costs associated with the loss of KCl were the largest ones, followed by  $P_2O_5$  and  $CaMg(CO_3)_2$ . The cost generated by the loss of nutrients in the soil with 0% cover totaled US\$ 107.76  $ha^{-1} year^{-1}$ . Of this amount, 37.75% correspond to  $P_2O_5$ , 53.26% to KCl and 8.99% to  $CaMg(CO_3)_2$ . In the soil with 24% cover, the cost was US\$ 71.67  $ha^{-1} year^{-1}$ , and losses of  $P_2O_5$ , KCl and  $CaMg(CO_3)_2$  corresponded respectively to 41.93%, 50.93% and 7.14% of this cost. In soil with 40% cover, the total cost was US\$ 35.38  $ha^{-1} year^{-1}$ , and losses of  $P_2O_5$ , KCl and  $CaMg(CO_3)_2$  contributed with 45.11%,

44, 01% and 10.88%, respectively, of this amount. In the soil with 90% cover, the total cost was US\$ 18.15  $ha^{-1} year^{-1}$ , and losses of  $P_2O_5$ , KCl and  $CaMg(CO_3)_2$  contributed, respectively, with 42.75%, 47% and 10.25% of the total.

#### 4. DISCUSSION

According to Lopes et al. (1987), Machado and Silva (2001) and Soane et al. (2012), soil cover rates with plant residues at 30% or more, during cultivation and fallow periods, characterize conservation management systems, with the ability to control the rainfall erosivity. In SPD with

100% soil cover, Cassol & Lima (2003) and Cassol et al. (2004) observed losses of soil and water ten times lower when compared to the bare soil (0% cover). Bertol et al. (2007) found that the PD, due to the greater soil cover, promoted 57% reduction in water loss and 88% in soil loss, compared to the PC.

Studies comparing management systems demonstrated that, in general, water losses are less influenced by soil cover than soil losses, as shown by De Maria (1999). Results of water loss have not shown a pattern; higher water losses are observed either in the PC, PM or PD, or are similar between the different systems, given the influence of factors other than soil cover, such as changes in the structure and in water infiltration rate. In the present study, in which only soil cover influenced the losses, the increase in soil cover rate controlled the losses of both soil and water. This means that the soil cover favored the retention of soil particles and water in the production unit.

Many indicators of soil quality are closely related to the OM, such as aggregate stability (Tisdall & Oades, 1982), infiltration and retention of water in the soil, cation exchange capacity (CEC), nutrient availability to plants (Bronick & Lal, 2005), among others. In this context, losses of soil OM caused by erosion have a negative effect on the chemical, physical and biological soil properties, expressed mainly by reducing its fertility by reducing the productivity of the soil (Lal, 1998; Den Biggelaar et al., 2003a, b) and the vicious circle of accelerated erosion. Furthermore, soil erosion contributes to the release of CO<sub>2</sub>, which impacts negatively on climate change (Lal, 2004). The persistence of this process can lead agricultural activities, ultimately, to a situation of economic unsustainability, mainly because the farmer tries to make up for the loss of soil quality with a higher volume of inputs, which results in higher production costs - and the replacement of soil OM is not feasible in the short term. In this way, the attempt of economically valuing quality loss is risky, with high risk of estimation errors. Conservation management systems, such as PD, provide lower losses of soil OM (Hernani et al., 1999), and its benefits occur in the long term, depending on their dynamics.

Regarding the loss of macronutrients (P, K<sup>+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup>), the values were high (Table 3), especially P in runoff water, which can also result in eutrophication (Boardman & Poesen, 2006; Ekholm & Lehtoranta, 2012). However, soil cover was more effective in controlling losses of these nutrients in runoff water than in eroded sediments.

When considering the amount of fertilizer lost in relation to that applied by the farmers in annual crops, values were high (Table 5). For instance, the amount of fertilizer recommended by van Raij et al. (1996) to obtain yield of 6-8 t ha<sup>-1</sup> of maize and 3-3.5 t ha<sup>-1</sup> of soybean (70 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub> and 103 kg ha<sup>-1</sup> KCl), and comparing

these values to the results herein, it can be concluded that in the treatment without soil cover, the loss would be 16% P<sub>2</sub>O<sub>5</sub> and 8% KCl, and in the treatment with 90% cover, 5% P<sub>2</sub>O<sub>5</sub> and 2% KCl. The difference between the treatments of 0% and 90% indicates a reduction in the loss of fertilizer, which allows farmers to choose to keep the cover on the soil - by planting cover crops or by crop rotation, like the SPD - guided by the economic rationality. Considering the amount of limestone customarily applied (≥ 2,000 kg ha<sup>-1</sup>), the losses observed in this study were proportionally low (90.55 kg ha<sup>-1</sup>).

Besides that, losses of micronutrients were very low (Table 4), so that there was no effect from the treatments of soil cover. Thus, to avoid underestimation errors, costs were not estimated.

The costs associated with the losses of P, K<sup>+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup>, expressed as P<sub>2</sub>O<sub>5</sub> (42%), KCl (60%) and CaMg (CO<sub>3</sub>)<sub>2</sub> (38%), in this study, were always lower the greater the soil cover rate. Losses of K<sup>+</sup>, in the form of KCl (60%), as well as in the study of Bertol et al. (2007), impacted most the on-site costs of soil erosion. In general, the results indicate that the higher the soil cover percentage, the lower the costs of erosion associated with total losses of nutrients, i.e., both in runoff water and in eroded sediments.

In Brazil, examples of this finding are reported in Bertol et al. (2007) and Pugliesi et al. (2011), who verified a reduction of losses generated by erosion in management systems with greater soil cover. In the first case (Bertol et al., 2007), the authors estimated the costs of soil erosion associated with nutrient losses, converted into triple superphosphate, potassium chloride and dolomitic limestone, in three management systems (PC, PM and PD) on a Cambisol. The values estimated in PC were 40.53% higher than in PD. In the second study (Pugliesi et al., 2011), the authors presented the costs related to loss of nutrients, expressed in the form of urea, simple superphosphate, potassium chloride and dolomitic limestone, on a Latosol, undulating relief, for different management systems. The estimates indicated that the costs in PC were 140% higher than in PD.

Moreover, both the losses and costs are annual, having a cumulative effect. When the soil is exposed for a long period to erosion, the volume of inputs necessary to return what is lost, in order to restore soil fertility to rates that ensure an adequate productivity, can be costly and even economically feasible. Therefore, maintenance of soil cover is essential to minimize the negative effects of erosion on agricultural lands.

In the specific case of this study, we presented the costs related to the loss of some macronutrients. If the replenishment of nutrients transported by erosion is necessary to maintain soil fertility at a level that ensures adequate production, additional costs must be computed with labor, machinery and fuel, to perform this procedure.

With regard to debate on the importance of valuing the on-site costs of soil erosion considering the loss of nutrients (which is a small portion of the total cost), it can be said that although it is an underestimation of the real cost of erosion, the results generated are valid and of great importance, especially in developing countries, and mainly when those values are expanded to larger territorial units such as cities, states, country. In addition, there are few studies on this topic, and it is necessary and desirable to advance this line of research in Brazil.

For Brazil, for example, Bahia et al. (1992) estimated erosion losses in agricultural areas at 600 million tons of soil per year, amounting to US\$ 1.5 billion according to nutrient losses. In turn, Hernani et al. (2002) estimated the losses at 820 million tons of soil per year, with a total cost of US\$ 2.64 billion with losses of nutrients, which represented approximately 7% of Gross Domestic Product (GDP) of agriculture in 2000.

If we consider the estimates of soil losses and costs observed in this study, assuming the artificial soil cover of 24% as equivalent to PC, 40% to PM and 90% to SPD, and based on the numbers published by Llanillo et al. (2013) in relation to the area planted with annual crops by these tillage systems in Brazil<sup>(5)</sup>, in 2006<sup>(6)</sup>, it is possible to estimate losses of soil for the country at approximately 616.5 million of tons per year, with a total annual cost<sup>(7)</sup> with the losses of P, K<sup>+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup>, expressed as P<sub>2</sub>O<sub>5</sub> (42%), KCl (60%) and CaMg(CO<sub>3</sub>)<sub>2</sub> (38%), of around US\$ 1.3 billion<sup>(8)</sup>. The difference of these values from those presented by Bahia et al. (1992) and Hernani et al. (2002) is that these authors considered, beyond the areas of annual crops, those areas used with pastures and perennial crops, totaling a larger area than that considered in this study.

From the differences obtained between the different cover rates, considering the possibility that the whole area of annual crops in Brazil were grown under PD, estimation of soil losses for the country would be about 420.3 million tons per year, with a total annual cost of the losses of P, K<sup>+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup>, expressed as P<sub>2</sub>O<sub>5</sub> (42%), KCl (60%) and CaMg(CO<sub>3</sub>)<sub>2</sub> (38%), at US\$ 603.6 million.

From the farmer point of view, losses and costs are barely noticeable, but, considering the whole Brazilian agriculture, the values are high and justify the importance of using soil cover, among other factors

<sup>(5)</sup> This information is for the 2006 Agricultural Census, by the Brazilian Institute of Geography and Statistics – IBGE (Llanillo et al., 2013).

<sup>(6)</sup> PC: 11,784.213 ha; PM: 3,783.494 ha; SPD: 17,871.773 ha.

<sup>(7)</sup> These estimates consider only the monetary amounts that would have been paid by farmers for the lost nutrients and do not consider broadly replacement costs, because there is no analysis of the amount required to replenish in terms of nutrients to restore soil fertility in order to achieve maximum yield.

<sup>(8)</sup> In dollars on March 3<sup>rd</sup>, 2011.

## 5. CONCLUSION

Comparing to the bare soil (0% cover), the soil with 90% cover reduced the average losses of water, soil and OM by 51.97%, 54.44%, and 54.89%, respectively.

The highest soil cover percentage resulted in lower costs associated with losses of water, soil and nutrients by erosion.

Soil erosion costs associated with the loss of fertilizers for the rates of 0%, 24%, 40% and 90% soil cover were, respectively, US\$ 107.76, US\$ 71.67, US\$ 35.38 and US\$ 18.15 per ha<sup>-1</sup> year<sup>-1</sup>.

As to bare soil, losses were estimated at 16% for P<sub>2</sub>O<sub>5</sub> and 8% for KCl in relation to the recommended amount of fertilizer.

Based on the presented results, it is estimated that soil erosion costs related to losses of P, K<sup>+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup>, in annual crops in Brazil, would be around US\$ 1.3 billion a year.

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