RESIDUAL EFFECT OF SOIL TILLAGE ON WATER EROSION FROM A TYPIC PALEUDALF UNDER LONG-TERM NO-TILLAGE AND CROPPING SYSTEMS[1]

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SUMMARY

Soil erosion is one of the chief causes of agricultural land degradation. Practices of conservation agriculture, such as no-tillage and cover crops, are the key strategies of soil erosion control. In a long-term experiment on a Typic Paleudalf, we evaluated the temporal changes of soil loss and water runoff rates promoted by the transition from conventional to no-tillage systems in the treatments: bare soil (BS); grassland (GL); winter fallow (WF); intercrop maize and velvet bean (M+VB); intercrop maize and jack bean (M+JB); forage radish as winter cover crop (FR); and winter cover crop consortium ryegrass - common vetch (RG+CV). Intensive soil tillage induced higher soil losses and water runoff rates; these effects persisted for up to three years after the adoption of no-tillage. The planting of cover crops resulted in a faster decrease of soil and water loss rates in the first years after conversion from conventional to no-tillage than to winter fallow. The association of no-tillage with cover crops promoted progressive soil stabilization; after three years, soil losses were similar and water runoff was lower than from grassland soil. In the treatments of cropping systems with cover crops, soil losses were reduced by 99.7 and 66.7 %,

compared to bare soil and winter fallow, while the water losses were reduced by 96.8 and 71.8 % in relation to the same treatments, respectively.

Index terms: cover crops, water runoff, soil erosion.

RESUMO: *EFEITO RESIDUAL DO PREPARO DO SOLO SOBRE A EROSÃO HÍDRICA EM UM ARGISSOLO VERMELHO SOB PLANTIO DIRETO E SISTEMAS DE CULTURAS DE LONGA DURAÇÃO*

Erosão ainda causa degradação do solo em todo o mundo e é uma das mais importantes fontes de poluição ambiental. Para atenuar esse problema, a mudança de manejo do solo é indicada, e o sistema plantio direto é a principal ferramenta utilizada. Com o objetivo de avaliar as alterações temporais das taxas de escoamento da água e das perdas de solo provocadas pela transição do preparo convencional do solo para o sistema plantio direto (SPD), um experimento de longa duração foi conduzido em um Argissolo Vermelho distrófico, na Universidade Federal de Santa Maria, RS, Brasil. Os tratamentos testados foram: BS - solo descoberto; GL - campo nativo; WF - pousio invernal; M+VB - consórcio de milho e mucuna-preta; M+JB - consórcio de milho e feijão de porco; FR - nabo forrageiro como cultura de cobertura de inverno; e RG+CV - consórcio de culturas de cobertura de inverno, azevém e ervilhaca. Os resultados evidenciaram que o preparo do solo promoveu aumento da erosão e do escoamento da água; consequentemente, os efeitos desses permaneceram significativos pelo menos três anos após a adoção do SPD. Também apresentaram que o uso de culturas de cobertura de inverno ou de verão gerou estabilização mais rápida do solo, bem como menores perdas de solo e água do que o pousio invernal, nos primeiros anos após o preparo do solo. O SPD associado a plantas de cobertura do solo ocasionou a estabilização progressiva do solo; após três anos de sua implantação, a perda de solo foi semelhante e o escoamento de água foi menor, em comparação ao solo sob campo nativo. O uso de culturas de cobertura de inverno ou de verão reduziu a perda de solo, em 99,7 e 66,7 %, e do escoamento de água, em 96,8 e 71,8 %, em comparação ao solo descoberto e o pousio invernal, respectivamente.

Termos de indexação: plantas de cobertura, escoamento superficial de água, erosão do solo.

INTRODUCTION

Soil erosion is the main cause of land degradation (Eswaran et al., 2001; Lal, 2001) and one of the major environmental and food security threats mankind is facing (Pimentel, 2006). Slight to moderate soil erosion can increase crop yield losses by 0.6 to 2.8 % for each centimeter of eroded topsoil (Langdale et al., 1979; Albuquerque et al., 1996; Duan et al., 2011). About 10 million hectares of cropland are abandoned worldwide every year due to the depletion of crop yields by severe soil erosion (Faeth & Crosson, 1994). However, the increasing food demand of the growing world population will require an additional 1 billion hectares of agricultural lands by 2050 (Tilman et al., 2001). This process increases the pressure on agriculture soils to ensure food security and water quality and to meet emerging environmental demands, as for renewable energy production and mitigation of climate change (Lal, 2007).

Croplands are especially susceptible to soil erosion under intensive and frequent soil tillage or exposure of bare soil to rain. When soil is tilled and turned, the potential for accelerated soil loss increases (Triplett & Dick, 2008). Conventional tillage (CT) increases soil particle detachment and transportation by soil splash

(Reichert & Cabeda, 1992; Choudhary et al., 1997), increasing surface sealing, water runoff and, consequently, reducing water infiltration (Cogo et al., 2003; Guadagnin et al., 2005; Amaral et al., 2008; Strudley et al., 2008). The introduction of no-tillage (NT) systems in crop and residue management is a key strategy for reducing soil erosion and water runoff in agriculture (Schuller et al., 2007).

Several mechanisms are related to the reduction of soil erosion under NT, including the absorption of the kinetic energy of raindrops by a plant cover on the soil surface, preventing the detachment of soil particles, reducing the erodibility of undisturbed soil and water flow on the soil surface and increasing water infiltration into the soil (Debarba, 1993; Triplett & Dick, 2008). The efficiency of NT systems in decreasing soil and water losses is based on the use of cover crops in cropping systems (Schick et al., 2000a,b; Seganfredo et al., 1997). Comparisons between long-term plots and field-scale assessments showed net reductions in soil erosion rates of 19 to 91 % under NT in relation to CT (Choudhary et al., 1997; Cogo et al., 2003; Guadagnin et al., 2005; Schuller et al., 2007).

A nationwide assessment of soil erosion from US croplands showed that soil losses due to water erosion dropped from 9.9 to 6.7 Mg ha^{-1} yr^{-1} or 32 % between

1982 and 2007 (NRCS, 2010). This result could be partially explained by the increase in NT area from 2.5 to 16.1 % of US croplands between 1984 and 2007 (FAO, 2011). A recent study showed that soil erosion rates in a cropland from Chile decreased from 11.0 to 1.4 Mg ha^{-1} yr^{-1} or 87 %, 18 years after CT-NT conversion (Schuller et al., 2007). However, there is a lack of information about how much time is necessary for soil stabilization and to reduce soil and water losses after NT conversion. The objective of this work was to evaluate temporal changes of soil erosion and water runoff rates from a Typic Paleudalf in Southern Brazil, after the conversion of grassland to CT crops and the following adoption of NT with different cropping systems.

MATERIAL AND METHODS

This long-term experiment was carried out at the experimental station of the Soil Department of the Federal University of Santa Maria, Rio Grande do Sul, Brazil. The local climate is humid subtropical (Köppen Cfa), with mean annual rainfall and temperature of 1,500 mm and 18.5 °C, respectively. The soil was a Typic Paleudalf (USDA, 1999) with the following properties (0-0.20 m layer) at the beginning of the experiment: 87 g kg^{-1} clay; 660 g kg^{-1} sand; 253 g kg^{-1} silt; pH (H$_2$O) = 4.50; P = 1.80 mg dm^{-3}; K = 33 mg dm^{-3}; O.M.= 24.6 g kg^{-1}; Al = 1.4 mmol$_c$ dm^{-3}; Ca + Mg = 2.6 cmol$_c$ dm^{-3}; and CEC = 4.08 cmol$_c$ dm^{-3} (Debarba, 1993).

The experiment was installed on a grassland area in March 1991, in a completely randomized design with seven treatments and two replications. The treatments consisted of: bare soil - BS; grassland - GL; winter fallow - WF; intercrop maize (*Zea mays* L.) and velvet bean (*Stizolobium cinereum* Piper & Tracy) - M+VB; intercrop maize and jack bean [*Canavalia ensiformis* (L.) DC.] - M+JB; forage radish (*Raphanus sativus* L.) as winter cover crop - FR; winter cover crop consortium of ryegrass (*Lolium multiflorum* Lam.) and common vetch (*Vicia sativa* L.) - RG+CV (detailed descriptions see Table 1). At that time, 6.5 Mg ha^{-1} lime and 130 kg ha^{-1} P$_2$O$_5$ were applied and plowed into the soil by disk plowing followed by two tandem disk operations, except in the GL treatment, which was not fertilized. Afterwards no-tillage was adopted for all cropping systems. Each plot (width 3.5 m, length 22 m) was marked by galvanized steel sheets (height 0.20 m), driven into the soil to a depth of 0.10 m. The average plot slope was 0.055 m m^{-1}.

Soybean and maize were sown with a hand-held seeder at a density of, respectively, 250.000 and 60.000 plants ha^{-1}. Velvet and jack beans as intercrop after maize were sown in hoe-dug grooves at a density of 40 and 60 kg ha^{-1} seeds, respectively. All crop rows ran perpendicular to the soil slope. Ryegrass, common

vetch and forage radish seeds (20, 30 and 20 kg ha^{-1}, respectively) seeds were broadcast by hand on plots without subsequent incorporation. Soybean and maize were fertilized according to the recommendations of CQFSRS/SC (2004).

Soil and water losses were first measured in April 1992, after the installation of covered collecting spouts at the lower end of the plots, which were connected to 1 m^3 collection tanks by 75 mm PVC pipes. On the BS plots, a second collection tank was installed due to the high volume of water runoff and soil erosion from that treatment. The two collection tanks were connected through GEIB divisors to collect only 1/9 of the water volume. Soil losses were measured according to the method of Veiga & Wildner (1993) after each rainfall or group of rainfall events. Considering the variations in soil slope between plots, soil losses were adjusted to a standard slope of 0.06 m m^{-1} (Wischmeier & Smith, 1978). Rainfall data were collected at a meteorological station at a distance of 2 km from the experimental area. Rain erosivity was determined by the EI30 index, calculated as proposed by Wischmeier & Smith (1978) with modifications by Cabeda (1976). The rain erosivity data were converted to the international unit system as described by Foster et al. (1981).

Analysis of variance (ANOVA) was performed using SAS PROC MIXED (SAS Institute, 2002) to assess differences in soil and water losses among treatments. The ANOVA was performed comparing all treatments and also with exclusion of the BS treatment from the comparisons, since the high soil and water losses from bare soil limited the sensitivity of the statistical analysis to detect differences among the other treatments. The residual effects of soil tillage on water erosion were evaluated by temporal changes in soil and water losses from each treatment by regression analysis of soil and water losses over time, using software TableCurve 2D v5.01 (Systat Software Inc., Richmond, CA 94804-2028). Treatments with significant changes in soil and water loss rates over time were subjected to a new ANOVA to assess differences among treatments and evaluation periods (group of years). The periods were established based on the results of regression analysis which showed periods with distinct patterns of soil and water losses over time. Means were compared using differences in least square means. Results were considered statistically significant at p<0.05.

RESULTS AND DISCUSSION

Annual and total soil losses

After 16 years, 2,539.7 Mg ha^{-1} of soil were lost from the BS treatment (Table 2). Considering an average soil bulk density of 1.51 Mg m^{-3} in the 0-0.16 m layer of the BS plots at the beginning of the

Table 1. Description of cropping systems used in a long-term soil erosion experiment

Year[1]	Treatment						
	BS[2]	WF	M+VB	M+JB	FR	RG+CV	GL
1991-1992	WF/Maize	GP/Maize	WF/M+VB	WF/M+JB	BL/Maize	BO+CV/Maize	Grassland
1992-1993	Bare soil	WF/Maize	WF/M+VB	WF/M+JB	BL/Maize	BO+CV/Maize	Grassland
1993-1994	Bare soil	WF/Maize	WF/M+VB	WF/M+JB	BL/Maize	BO+CV/Maize	Grassland
1994-1995	Bare soil	WF/Soybean	WF/Sunflower+VB	WF/Sunflower+JB	RG/Soybean	BO/Soybean	Grassland
1995-1996	Bare soil	WF/Maize	WF/M+VB	WF/M+JB	FR/Maize	RG+CV/Maize	Grassland
1996-1997	Bare soil	WF/Soybean	WF/CB+VB	WF/CB+JB	RG/Soybean	BO/Soybean	Grassland
1997-1998	Bare soil	WF/Maize	WF/M+VB	WF/M+JB	FR/Maize	RG+CV/Maize	Grassland
1998-1999	Bare soil	WF/Maize	WF/M+VB	WF/M+JB	BO/Maize	RG/Maize	Grassland
1999-2000	Bare soil	WF/Maize	WF/M+VB	WF/M+JB	FR/Maize	RG+CV/Maize	Grassland
2000-2001	Bare soil	WF/Maize	WF/M+VB	WF/M+JB	FR/Maize	RG+CV/Maize	Grassland
2001-2002	Bare soil	WF/Soybean	WF/Soybean	WF/Soybean	FR/Soybean	RG+CV/Soybean	Grassland
2002-2003	Bare soil	WF/Maize	WF/M+VB	WF/M+JB	FR/Maize	RG+CV/Maize	Grassland
2003-2004	Bare soil	WF/Soybean	WF/Soybean	WF/Soybean	FR/Soybean	RG+CV/Soybean	Grassland
2004-2005	Bare soil	WF/Maize	WF/M+VB	WF/M+JB	FR/Maize	RG+CV/Maize	Grassland
2005-2006	Bare soil	WF/Soybean	WF/Soybean	WF/Soybean	FR/Soybean	RG+CV/Soybean	Grassland
2006-2007	Bare soil	WF/Maize	WF/M+VB	WF/M+JB	FR/Maize	RG+CV/Maize	Grassland
2007-2008	Bare soil	WF/Soybean	WF/Soybean	WF/Soybean	FR/Soybean	RG+CV/Soybean	Grassland

[1] Corresponding to the period from April of the first year to March of the following year. [2] BS: Bare soil; WF: Winter fallow; Maize: *Zea mays* L.; GP: Grass Pea (*Lathyrus sativus* L.) Soybean: *Glycine max* (L.) Merrill; M+VB: Intercrop maize - velvet bean (*Stizolobium cinereum* Piper & Tracy); Sunflower+VB: Intercrop of Sunflower (*Helianthus annuus* L.) and Velvet Bean; CB+VB: Intercrop of Commom Bean (*Phaseolus vulgaris* L.) and Velvet Bean; M+JB Intercrop of Maize and Jack Bean (*Canavalia ensiformis* (L.) DC.); Sunflower+JB: Intercrop of Sunflower and Jack Bean; CB+JB: Intercrop of Commom Bean and Jack Bean; FR: Forage Radish (*Raphanus sativus* L.); BL: Blue Lupine (*Lupinus angustifolius* L.); RG: Ryegrass (*Lolium multiflorum* Lam.); BO: Black oat (*Avena strigosa* Schreb.); RG+CV: winter consortium ryegrass - common vetch (*Vicia sativa* L.); BO+CV: winter consortium of Black Oat and Common Vetch.

experiment (Lanzanova et al., 2010), an estimated 0.168 m of soil were eroded from this treatment by water. Annual soil losses from the BS were significantly higher than in all other treatments, with exception of the period from 2004 to 2005, when rainfall volume and erosivity were very low (925 mm and 3,919 MJ mm ha^{-1} h^{-1}, respectively) in comparison to the average rainfall volume and erosivity measured in the 16 experimental years (1,663 mm and 7,891 MJ mm ha^{-1} h^{-1}, respectively). Total soil loss from BS was 125 and 1,149 times higher than in the treatments WF and GL, respectively.

The huge soil losses from BS, several times higher than in the other treatments, limited the ANOVA sensitivity to detect the small differences between NT and GL treatments. When excluding the BS treatment from the statistical analysis, ANOVA and the LS means test were able to detect significant differences in soil erosion in the first two years of the experiment and in total soil losses accumulated over 16 years of measurement in the other treatments. In 1992-1993 and 1993-1994, more soil was lost from the treatment WF than from the other NT treatments and GL, which did not differ from each other. The higher soil losses from WF were probably due to the lack of soil cover in that treatment in the first years after soil tillage. Soil losses were lower from the other NT treatments with summer and winter cover crops, not differing from GL even in the first years after soil tillage.

Total soil losses from the treatment WF were also significantly higher than in the other NT treatments and GL. This result was mostly related to the higher soil erosion rates in this treatment in the first two years after soil tillage at the beginning of the experiment, which accounted for 79.6 % of the total soil losses verified after 16 years. Total soil losses from summer (M+VB and M+JB) and winter (FR and RG+CV) cover crop treatments were statistically similar to each other, but only winter cover crop treatments had soil losses close to GL. The treatments FR and RG+CV had live plants covering the soil during great part of the year, while in the treatments M+VB and M+JB the plants grew only in the summer period. The lack of growing plants in the winter could explain the slightly higher soil losses from M+VB and M+JB. Soil losses in the first two years after soil tillage in NT treatments ranged from 36.2 to 47.4 % of the total soil loss after 16 years, while (not tilled) only 11.3 % of the total soil losses from GL were recorded in the first two years after the beginning of the experiment. There was a clear residual effect of soil tillage at the beginning of the experiment, which affected soil losses in the first evaluation years. Similar results were reported by Oliveira et al. (2012). These effects were analyzed by regression analysis assessing

Table 2. Soil losses in a long-term experiment, comparing bare soil, grassland and cropping systems

Year[1]	Rain erosivity	Soil loss from treatment[2]						
		BS	WF	M+VB	M+JB	FR	RG+CV	GL
	MJ mm ha^{-1} h^{-1}	Mg ha^{-1}						
1992-1993	7,919	171.77 a	6.47 bA	1.83 bB	1.65 bB	1.87 bB	0.53 bB	0.18 bB
1993-1994	2,350	220.15 a	9.63 bA	1.42 bB	1.36 bB	1.20 bB	0.86 bB	0.07 bB
1994-1995	3,436	182.42 a	1.25 b^{NS}	0.73 b	0.76 b	1.09 b	0.53 b	0.21 b
1995-1996	8,274	96.20 a	0.16 b^{NS}	0.80 b	1.66 b	0.11 b	0.23 b	0.12 b
1996-1997	5,920	51.23 a	0.11 b^{NS}	0.15 b	0.32 b	0.03 b	0.04 b	0.08 b
1997-1998	11,798	184.29 a	0.44 b^{NS}	0.60 b	0.81 b	0.20 b	0.16 b	0.19 b
1998-1999	11,983	125.74 a	0.39 b^{NS}	0.09 b	0.23 b	0.26 b	0.09 b	0.14 b
1999-2000	8,879	114.61 a	0.15 b^{NS}	0.13 b	0.15 b	0.05 b	0.12 b	0.09 b
2000-2001	11,498	206.98 a	0.14 b^{NS}	0.04 b	0.08 b	0.03 b	0.08 b	0.15 b
2001-2002	10,667	174.53 a	0.08 b^{NS}	0.11 b	0.04 b	0.04 b	0.03 b	0.10 b
2002-2003	12,628	243.30 a	0.48 b^{NS}	0.09 b	0.11 b	0.11 b	0.33 b	0.24 b
2003-2004	9,025	144.64 a	0.07 b^{NS}	0.05 b	0.05 b	0.03 b	0.13 b	0.15 b
2004-2005	3,919	10.69 ^{ns}	0.02 ^{NS}	0.04	0.01	0.05	0.01	0.08
2005-2006	6,059	285.54 a	0.46 b^{NS}	1.97 b	0.19 b	0.50 b	0.13 b	0.13 b
2006-2007	6,477	142.42 a	0.22 b^{NS}	0.28 b	0.33 b	0.76 b	0.06 b	0.16 b
2007-2008	5,435	185.22 a	0.14 b^{NS}	0.35 b	0.20 b	0.16 b	0.53 b	0.11 b
Sum	126,26	2,539.73 a	20.22 bA	8.67 bB	7.94 bB	6.48 bBC	3.84 bBC	2.21 bC

[1] Corresponding to the period from April of the first year to March of the following year. [2] BS: bare soil; WF: winter fallow; M+VB: intercrop maize - velvet bean; M+JB: summer consortium maize - jack bean; FR: forage radish; RG+CV: winter consortium ryegrass - common vetch; GL: grassland. Means followed by the same lowercase letter in the same year are not different by the LS means test (p<0.05) in the comparison among all treatments; means followed by the same uppercase letter in the same year are not different by the LS means test (p<0.05) in the comparison of treatments WF, M+VB, M+JB, FR, RG+CV, and GL; ^{ns} not significant by the F test (p>0.05) in the comparison among all treatments; ^{NS} Not significant by the F test (p>0.05) in the comparison of the treatments WF, M+VB, M+JB, FR, RG+CV, and GL.

temporal changes in soil erosion under different cropping systems.

Temporal changes in soil loss rates

Soil losses remained stable in the treatments BS and GL over the whole evaluation period, with annual soil erosion rates of 158.7 and 0.14 Mg ha^{-1} yr^{-1}, respectively (Figure 1). However, temporal analysis of soil losses from NT treatments showed a distinct pattern, of rapid decreases in the first years after soil tillage and stabilization thereafter, with very similar soil erosion rates to those in the GL treatment. The point of maximum curvature of the regressions adjusted to the soil loss data in NT treatments could be used as an indicator of how long soil tillage affected soil erosion in those treatments.

In all NT treatments, the point of maximum curvature of the regressions was close to the third year after soil tillage, with the exception of RG+CV, in which this point was closer to the second year after soil tillage. Up to three years were necessary for soil stabilization after tilling at treatment installation. The winter cover crops ryegrass and common vetch were efficient to accelerate soil stabilization and soil erosion control, even in the first two years after soil tillage, probably due to the quick growth and persistence of

ryegrass biomass, sustaining the conclusions of Schäfer et al. (2001) and Alves & Cabeda (1999).

Average soil erosion rates of the first three years (1992-1995) and the last 13 years (1995-2008), after soil stabilization, were statistically distinct for the treatments WF, M+VB, M+JB and FR (Table 3). No significant differences in soil erosion rates between the two periods were observed in the treatments BS, RG+CV and GL. In the period from 1992 to 1995, the soil erosion rates in NT treatments with summer or winter cover crops were similar, ranging from 0.63 to 1.32 Mg ha^{-1} yr^{-1}, but lower than in WF (5.78 Mg ha^{-1} yr^{-1}) and higher than in GL (0.15 Mg ha^{-1} yr^{-1}), respectively. In the period from 1995 to 2008, no significant differences in soil erosion rates were noticed between the treatments NT and GL.

These results suggest that after soil stabilization in the first two or three years after the last tillage operation, the NT system could control soil erosion with the same efficiency as grassland. Considering the average soil erosion rate in the BS treatment (158.7 Mg ha^{-1} yr^{-1}), NT treatments could control 96.3 to 99.6 % of the soil losses in the first three years after conversion of CT to NT. After soil stabilization, the average erosion control in the NT treatments and
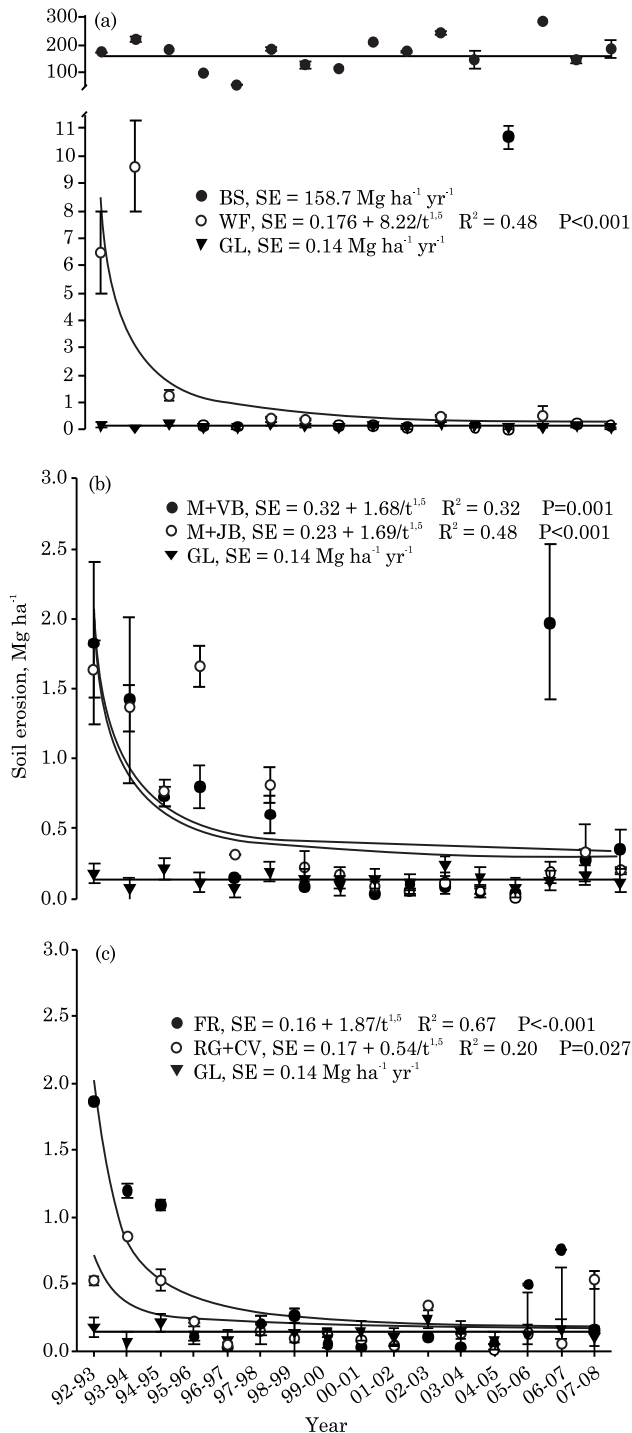
Figure 1. Soil losses from treatments BS, WF and GL (a) M+VB, M+JB and GL (b) and FR, RG+CV and GL (c) treatments as a time function (years) in a long-term experiment in Santa Maria, RS, Brazil. Vertical bars are mean standard errors (n=2). BS: Bare soil; WF: Winter fallow; M+VB: intercrop maize - velvet bean; M+JB: summer consortium maize - jack bean; FR: forage radish; RG+CV: winter consortium ryegrass - common vetch; GL: grassland. Soil losses from GL treatment was repeated in all graphs for better comparisons.

GL was 99.8 % and 99.9 % in relation to BS, respectively. Panachuki et al. (2011) found very low soil losses, higher water infiltration and lower water runoff under NT than CT.

Annual and total water runoff

Between April 1992 and March 2008, a total of 8,615 mm of water was lost from the BS treatment by surface runoff (Table 4). Total water runoff from this treatment was significantly higher than from all NT treatments and GL, ranging from 9 to 27 times higher than water losses in the WF and M+JB treatments, respectively. The annual water losses from BS ranged from 14 to 56 % of the annual precipitation in the period, and from 0.4 to 15.9 %, 0.2 to 16.8 %, and 0.4 to 2.8 %, respectively, in the GL, WF and other NT treatments.

For water runoff data, the approach of removing the BS treatment from the statistical analysis to increase the sensitivity of ANOVA and LS means tests to detect differences among NT and GL treatments was not effective since the sensitivity was not significantly higher than in the analysis including all treatments. There were significant differences in annual water runoff between NT and GL treatments in the first six years after the beginning of the experiment and for the total water runoff over the whole 1992-2008 period. Higher water runoff rates were recorded in GL in the period from 1992 to 1996. This result could be associated with the natural relief from soil compaction under GL due to the absence of machinery traffic on these plots after April 1992. Soil bulk density measured in the 0-0.16 m soil layer of the GL treatment in 1992 was 1.56 Mg m^{-3}, and 1.42 Mg m^{-3} in the 0-0.15 m soil layer in 2008 (Lanzanova et al., 2010). Higher annual water losses (> 100 mm) were also recorded in the WF treatment in the first three years after soil tillage, while in the other NT treatments annual water runoff never exceeded 54 mm. Total water losses (1992-2008) from GL (968 mm) were similar to those from the WF treatment (980 mm) but both results were higher than water runoff measured in the other NT treatments (320 to 435 mm for the M+JB and M+VB treatments, respectively).

Temporal changes in water runoff rates

No temporal changes in water runoff rates were detected in the BS treatment, which averaged 538.4 mm yr^{-1} or 32.2 % of the mean annual rainfall (1,663 mm yr^{-1}) in the period from 1992 to 2008 (Figure 2). However, water losses from the GL treatment differed considerably. Higher but decreasing water runoff rates were noticed in the first years after the beginning of the experiment and stabilization thereafter. An increase in water infiltration due to the improvement of soil physical quality should be the main mechanism that reduced water losses from GL (Bertol et al., 2004). A similar pattern was observed in the WF treatment. In this

Table 3. Mean soil loss rate and water runoff in different periods in a long-term experiment, comparing bare soil, grassland and no-tillage cropping systems

Year[1]	Treatment[2]						
	BS	WF	M+VB	M+JB	FR	RG+CV	GL
	Soil loss rate[3]						
	Mg ha^{-1} year^{-1}						
1992-1995	191.44 a^{ns}	5.78 bxA	1.32 bxB	1.25 bxB	1.38 bxB	0.63 b^{ns}B	0.15 bC
1995-2008	151.18 a	0.22 by^{NS}	0.36 by	0.32 by	0.18 by	0.15 b	0.13 b
Mean	158.73 a	1.26 bA	0.54 bB	0.50 bB	0.41 bBC	0.24 bBC	0.14 bC
	Water runoff[4]						
	mm year^{-1}						
1992-1995	580.3 a^{ns}	202.2 bxA	32.7 c^{ns}C	29.6 c^{ns}C	50.1 cxB	37.1 c^{ns}C	195.7 bxA
1995-2008	528.8 a	28.7 byA	25.9 bAB	17.8 bB	14.9 byB	18.7 bB	29.3 byA
Mean	538.4 a	61.3 bA	27.2 cB	20.0 cB	21.6 cB	22.1 cB	60.5 bA

[1] Corresponding to the period between April of the first year and March of the following year. [2] BS: bare soil; WF: winter fallow; M+VB: intercrop maize - velvet bean; M+JB: summer consortium maize - jack bean; FR: forage radish; RG+CV: winter consortium ryegrass - common vetch; GL: grassland. [3] The periods of the treatments BS and GL were not compared since the regression analysis (Figure 1) detected no significant changes of soil loss rate over the years. [4] The periods in treatments BS and M+VB were not compared since no significant changes in water runoff rate over years were detected by regression analysis (Figure 2). Means followed by the same lowercase letter for the same period in the comparison among all treatments (a,b) or for the same treatment in the comparison of different periods (x,y) were not different by the LS means test ($p<0.05$). Means followed by the same uppercase letter for the same period are not different by the LS means test ($p<0.05$) in the comparison of treatments WF, M+VB, M+JB, FR, RG+CV, and GL. ^{ns} Not significant by the F test ($p>0.05$) in the comparison among periods at the same treatment; ^{NS} not significant by the F test ($p>0.05$) in the comparison of the treatments WF, M+VB, M+JB, FR, RG+CV, and GL for the same period.

Table 4. Water runoff in a long-term experiment, comparing bare soil, grassland and cropping systems

Year[1]	Rain	Water runoff from treatment[2]						
		BS	WF	M+VB	M+JB	FR	RG+CV	GL
		mm						
1992-1993	1,719	443.4 a	215.6 cB	42.1 dC	32.5 dC	54.1 dC	32.9 dC	272.8 bA
1993-1994	1,719	519.4 a	289.7 bA	28.3 cD	26.6 cD	47.7 cC	25.7 cD	119.8 bB[3]
1994-1995	1,993	778.0 a	101.4 cB	27.7 eD	29.6 eCD	48.6 deCD	52.7 dC	195.0 bA
1995-1996	1,244	578.1 a	33.9 cB	29.6 cBC	36.5 cB	16.1 cC	25.7 cBC	90.6 bA
1996-1997	1,100	209.3 a	6.2 cdBC	16.8 bcA	15.0 bcdAB	5.1 dC	6.7 cdBC	18.5 bA
1997-1998	1,934	743.5 a	54.5 bA	44.8 bcAB	37.1 bcBC	15.9 cD	29.9 bcC	35.5 bcBC
1998-1999	1,536	476.9 a	48.1 b^{NS}	19.2 b	18.3 b	16.0 b	23.7 b	22.7 b
1999-2000	1,458	431.0 a	10.3 b^{NS}	24.1 b	11.3 b	9.8 b	9.7 b	6.1 b
2000-2001	2,046	759.1 a	21.7 b^{NS}	20.4 b	21.0 b	14.3 b	22.7 b	29.1 b
2001-2002	1,805	743.9 a	45.3 b^{NS}	23.4 b	16.9 b	19.3 b	21.7 b	36.0 b
2002-2003	2,898	1,060.9 a	87.9 b^{NS}	51.5 b	28.8 b	43.9 b	45.7 b	45.1 b
2003-2004	1,452	512.3 a	30.5 b^{NS}	33.2 b	17.6 b	16.6 b	28.9 b	24.0 b
2004-2005	925	129.9 a	2.3 b^{NS}	7.7 b	2.9 b	3.0 b	2.5 b	3.7 b
2005-2006	1,860	410.3 a	6.1 b^{NS}	26.5 b	8.9 b	14.8 b	8.4 b	24.1 b
2006-2007	1,447	367.0 a	18.7 b^{NS}	21.3 b	8.1 b	11.3 b	6.6 b	28.9 b
2007-2008	1,476	452.4 a	7.9 b^{NS}	18.5 b	9.1 b	8.6 b	10.6 b	16.9 b
Sum	26,612	8,615.4 a	980.3 bA	435.0 cB	320.1 cB	345.0 cB	354.0 cB	968.8 bA

[1] Corresponding to the period from April of the first year to March of the following year. [2] BS: bare soil; WF: winter fallow; M+VB: intercrop maize - velvet bean; M+JB: summer consortium maize - jack bean; FR: forage radish; RG+CV: winter consortium ryegrass - common vetch; GL: grassland. [3] Water runoff in treatment GL was not measured in 1994, but estimated by regression analysis (Figure 2). Means followed by the same lowercase letter of the same year are not different by the LS means test ($p<0.05$) in the comparison among all treatments. Means followed by the same uppercase letter for the same year are not different by the LS means test ($p<0.05$) in the comparison of treatments WF, M+VB, M+JB, FR, RG+CV, and GL. ^{ns} Not significant by the F test ($p>0.05$) in the comparison among all treatments. ^{NS} Not significant by the F test ($p>0.05$) in the comparison of treatments WF, M+VB, M+JB, FR, RG+CV, and GL.
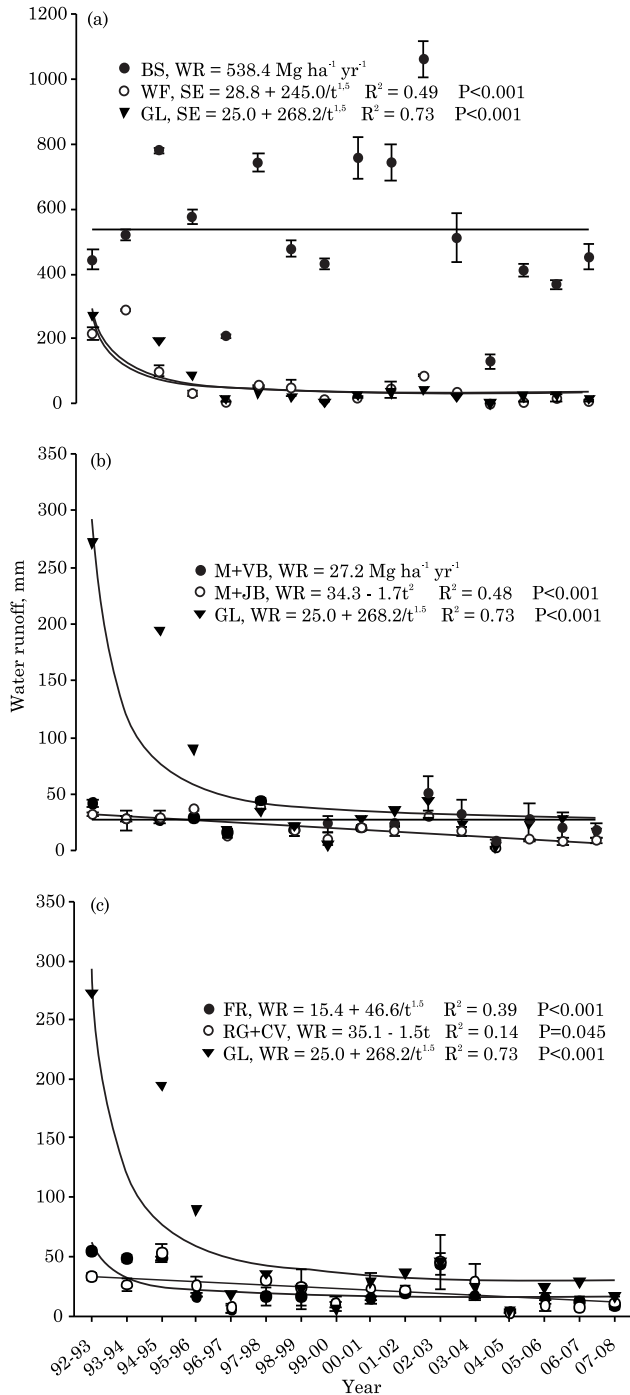
Figure 2. Water runoff from BS, WF and GL (a) M+VB, M+JB and GL (b) and FR, RG+CV and GL (c) treatments as a function of time (years) in a long-term experiment in Santa Maria, RS, Brazil. Vertical bars represents the mean standard error (n=2). BS: bare soil; WF: winter fallow; M+VB: summer consortium maize - velvet bean; M+JB: intercrop of Maize and Jack Bean; FR: Forage Radish; RG+CV: winter consortium ryegrass - common vetch; GL: grassland. Water runoff from GL was repeated in all graphs for better comparison of the results.

case, the higher water losses in the first three years after soil tillage could be the result of soil surface crusting under deficient soil cover by crop residues in that treatment. Similar results were also related by Derpsch et al. (1991) and (Panachuki et al., 2011).

Maize and velvet bean (M+VB) treatment showed no changes in water runoff rates throughout the experiment. Water losses from this treatment were lower in the first three years after soil tillage, and similar thereafter to the water losses from GL. The treatment FR showed small water loss rates during the whole period which decreased in the first three years and then stagnated. However, the water runoff rates I the treatments M+JB and RG+CV decreased continuously from 1992 to 2008, though the water loss rates were very low at the beginning of the experiment.

The average water runoff rates in the periods 1992-1995 and 1995-2008 are shown in table 5. No statistically significant differences among periods were noticed for the treatments BS, M+VB, M+JB, and RG+CV, while water loss rates were higher in the period from 1992 to 1995 for the treatments WF, FR and GL. Water runoff after soil tillage was faster and more efficiently controlled in M+VB, M+JB and RG+CV than in the other NT treatments, since water loss rates in these treatments were significantly lower than in WF and FR in the period from 1992 to 1995.

In the period from 1995 to 2008, water runoff rates in the treatments M+JV, FR and RG+CV were significantly lower than the rates in WF and GL, while M+VB had intermediary rates not differing from other treatments. The lower or similar water runoff rate in NT treatments than under GL could be associated with the higher soil macroporosity and roughness under NT than GL (Bertol et al., 2004; Luciano et al., 2009; Lanzanova et al., 2010).

CONCLUSIONS

1. Soil tillage promoted increases in soil erosion and water runoff and these effects remained significant for at least three years after the adoption of no-till system.

2. The use of winter or summer cover crops promoted faster soil stabilization and lower soil and water losses than winter fallow in the first years after soil tillage.

3. No tillage associated to cover crops promoted progressive soil stabilization and after three years, soil erosion was similar and water runoff was lower in comparison to the soil under grassland.

4. The use of winter or summer cover crops reduced soil erosion by 99.7 and 66.7 %, and water runoff by 96.8 and 71.8 %, compared to bare soil and winter fallow, respectively.

Table 5. Mean water runoff in different periods in a long-term experiment, comparing bare soil, grassland and no-tillage cropping systems

Year[1]	Treatment[2]						
	BS	WF	M+VB	M+JB	FR	RG+CV	GL
	mm year^{-1}						
1992-1995	580.3 a^{ns}	202.2 bxA	32.7 c^{ns}C	29.6 c^{ns}C	50.1 cxB	37.1 c^{ns}C	195.7 bxA
1995-2008	528.8 a	28.7 byA	25.9 bAB	17.8 bB	14.9 byB	18.7 bB	29.3 byA
Mean	538.4 a	61.3 bA	27.2 cB	20.0 cB	21.6 cB	22.1 cB	60.5 bA

[1] Corresponding to the period between April of the first year and March of the following year. [2] BS: bare soil; WF: winter fallow; M+VB: intercrop maize - velvet bean; M+JB: summer consortium maize - jack bean; FR: forage radish; RG+CV: winter consortium ryegrass - common vetch; GL: grassland. [3] The periods in treatments BS and M+VB were not compared since no significant changes in water runoff rate over years were detected by regression analysis (Figure 2). Means followed by the same lowercase letter for the same period in the comparison among all treatments (a,b) or for the same treatment in the comparison of different periods (x,y) were not different by the LS means test ($p < 0.05$). Means followed by the same uppercase letter for the same period are not different by the LS means test ($p < 0.05$) in the comparison of treatments WF, M+VB, M+JB, FR, RG+CV, and GL. ^{ns} Not significant by the F test ($p > 0.05$) in the comparison among periods at the same treatment; ^{NS} not significant by the F test ($p > 0.05$) in the comparison of the treatments WF, M+VB, M+JB, FR, RG+CV, and GL for the same period.

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