Revista
Brasileira de
Ciência do Solo

Division – Soil Use and Management | Commission – Soil and Water Management and Conservation

Soil physical properties and interrill erosion in agricultural production systems after 20 years of cultivation

Dorly Scariot Pavei(1), **Elói Panachuki**(1), **Júlio Cesar Salton**(1,2), **Jullian Souza Sone**(3)*, **Teodorico Alves Sobrinho**(4), **Wander Cardoso Valim**(5) and **Paulo Tarso Sanches de Oliveira**(4)

(1) Universidade Estadual de Mato Grosso do Sul, Departamento de Agronomia, Programa de Pós-Graduação em Agronomia, Aquidauana, Mato Grosso do Sul, Brasil.
(2) Empresa Brasileira de Pesquisa Agropecuária, Embrapa Agropecuária Oeste, Dourados, Mato Grosso do Sul, Brasil.
(3) Universidade de São Paulo, Escola de Engenharia de São Carlos, Programa de Pós-Graduação em Engenharia Hidráulica e Saneamento, São Carlos, São Paulo, Brasil.
(4) Universidade Federal de Mato Grosso do Sul, Faculdade de Engenharias, Arquitetura e Urbanismo e Geografia, Programa de Pós-Graduação em Tecnologias Ambientais, Campo Grande, Mato Grosso do Sul, Brasil.
(5) Universidade Federal da Grande Dourados, Faculdade de Ciências Agrárias, Programa de Pós-Graduação em Agronomia, Dourados, Mato Grosso do Sul, Brasil.

ABSTRACT: Agricultural management significantly influences soil physical properties and soil erosion. However, there are few studies investigating the long-term effects of agricultural management on soil erosion and physical properties. Here, we assessed the impacts of 20-year agricultural land uses under different management practices on soil physical properties and interrill erosion. This study was conducted on an experimental farm of the Embrapa Western Agriculture, Brazil, and the treatments consisted of soybean cropping under conventional tillage (CT) and no-tillage (NT), crop-livestock integration during the cropping phase (CL-C) and the livestock phase (CL-L), and *Brachiaria decumbens* pasture under rotational grazing (PP). Soil samples were taken to evaluate the soil physical properties, and 25 rainfall simulations with an intensity of 60 mm h^{-1} were carried out by using a portable rainfall simulator with runoff plots of 0.7 m^2 to quantify surface runoff and interrill erosion. After two decades, the crop-livestock systems (CL-L and CL-C) presented better soil physical properties in the topsoil layer (0.00–0.05 m) with a higher level of aggregation. Soil and water losses ranged from 4.7 to 14.4 × 10^{-3} kg m^{-2} and 4.9 to 12.4 mm, respectively. A higher reduction in soil erosion was observed in NT, while CT showed the highest soil erosion rates. These findings indicate an opportunity for a reduction of soil erosion by 60 % by adopting crop-livestock integration comparing CL-C with CT, while livestock under an integrated system (CL-L) decreased water loss by 30 % compared with PP. This study is a starting point for future research, and the findings reveal the potential to minimize the agriculture footprint.

Keywords: soil erosion, soil use and management, sustainable land use.

*** Corresponding author:**
E-mail: julliansone@usp.br

Received: May 05, 2021
Approved: July 16, 2021

How to cite: Pavei DS, Panachuki E, Salton JC, Sone JS, Alves Sobrinho T, Valim WC, Oliveira PTS. Soil physical properties and interrill erosion in agricultural production systems after 20 years of cultivation. Rev Bras Cienc Solo. 2021;45:e0210039.
https://doi.org/10.36783/18069657rbcs20210039

Editors: José Miguel Reichert and Gustavo Henrique Merten.

INTRODUCTION

Erosion is a surface process mainly influenced by soil physical conditions and is one of the processes of soil degradation accelerated by anthropic activity (Murphy and Fogarty, 2019). Several studies have investigated different strategies of agricultural management to improve soil fertility (Pham et al., 2018) and its physical properties (Dekemati et al., 2019), water availability (Almeida et al., 2018), and the control of water erosion (Sone et al., 2019). Sartori et al. (2019) estimated a global cost of eight billion US dollars to the global gross domestic product (GDP) per year due to soil erosion by water, negatively impacting food security worldwide. Healthy soil is of paramount importance to achieving food security (Vrese et al., 2018); therefore, understanding the impacts of different agricultural land uses on soil physical and chemical properties is critical for preventing soil erosion and increasing food production. For instance, Brazil presents an annual soil loss of 616.5 million tons, and it is estimated to incur US$ 1.3 billion per year due to the losses of P, K^+, Ca^{2+}, and Mg^{2+} (Dechen et al., 2015).

Production systems have been improved in recent decades so that conventional methods have lost ground to modern production and conservation systems such as no-till, intercropping, crop-livestock integration, crop-livestock-forest integration, and livestock-forestry integration. These systems involve diversification of agricultural production and crop rotation, leading to better water use conditions, increasing agricultural production, and improving soil quality (Almeida et al., 2018; Sone et al., 2019). Some studies have investigated the effects of different agricultural land uses and integration systems on soil physical and chemical properties (Salton et al., 2014; Cade-Menun et al., 2017; Zajícová and Chuman, 2019). These studies found that the use of the no-till and crop-livestock system can improve soil physical properties and, consequently, control soil erosion by water in the short, medium, and long term. Nevertheless, experimental information on the effects of integrated agricultural systems on soil physical properties and erosion in the long term is scarce. In turn, the lack of studies on agricultural land use impacts on soil properties and productivity has discouraged some farmers (Jose, 2009), and it undermines the advancement and application of innovative agricultural strategies that maintain soil health while increasing productivity.

The objective of this study was to investigate the effects of five agricultural management systems on soil physical properties and interrill erosion after 20 years of cultivation in a *Latossolo Vermelho Distrófico* (Ferralsol). A portable rainfall simulator was used to assess soil and water losses in cropping under (i) conventional tillage and (ii) no-tillage, (iii) rotational grazing, and crop-livestock integration under both (iv) crop and (v) livestock phases. Our findings contribute to a better understanding of the long-term effects of these agricultural land uses and management on soil physical properties and soil erosion. This study shows the promising alternative of adopting integrated systems to make agricultural production more sustainable.

MATERIALS AND METHODS

Study area

We carried out this study in the experimental area of the Embrapa Western Agriculture (Embrapa stands for Brazilian Agricultural Research Corporation), located in Dourados, Mato Grosso do Sul State (22° 16’ 55.0” S and 54° 48’ 18.1” W, 400 m of altitude) (Figure 1). Embrapa Western Agriculture has experimented with different crop-livestock integration systems since 1995.

The study area is in a transition strip between the Cerrado and the Atlantic Forest biomes, where the climate is classified as Cwa, a humid mesothermal climate with hot summers

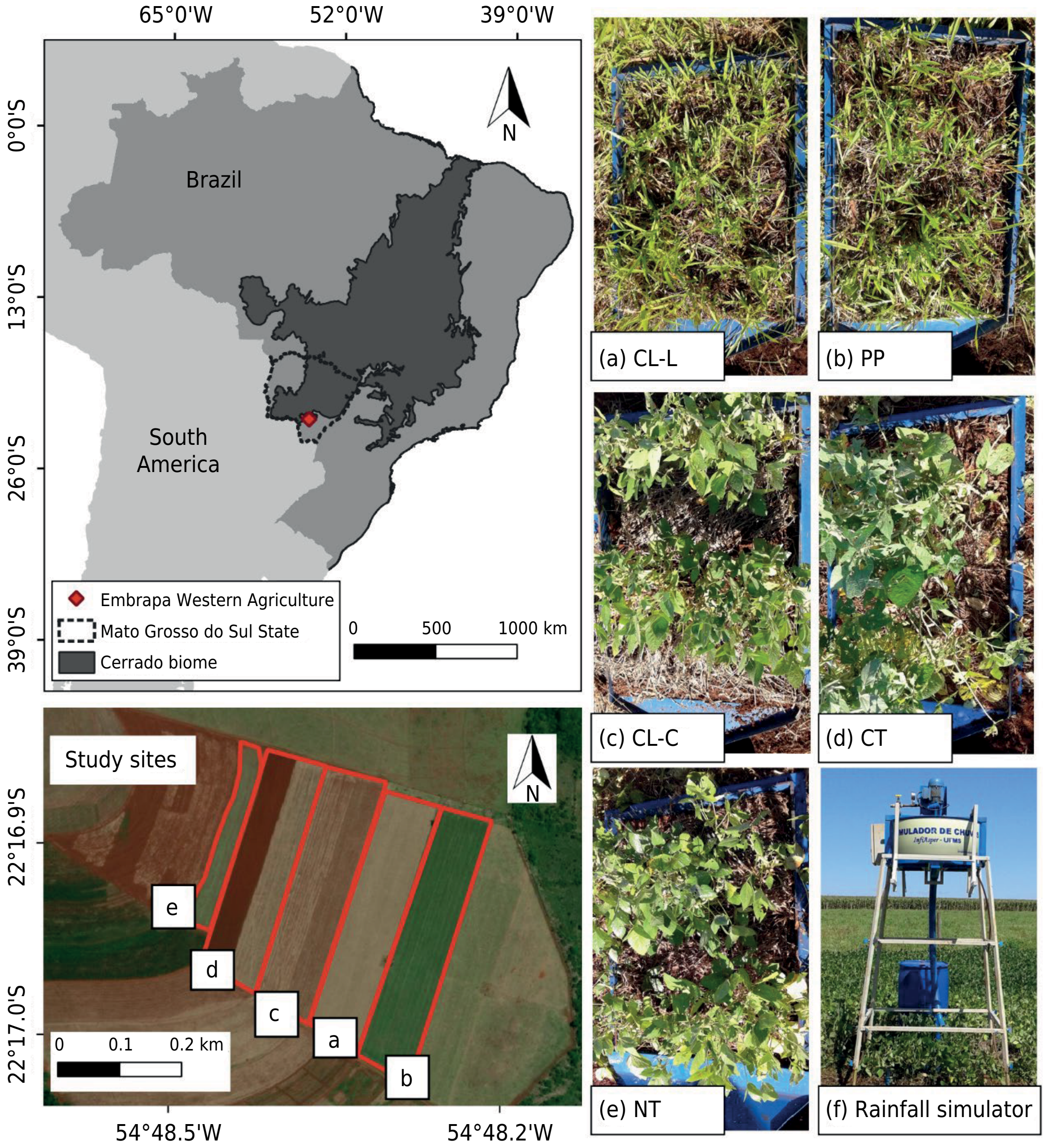

Figure 1. Location of the study area in a transition region between the Cerrado and the Atlantic Forest biomes, and (f) portable rainfall simulator used in the evaluations and the different agricultural land use systems: (a) crop-livestock integration in the livestock phase (CL-L), (b) Brachiaria decumbens permanent pasture under rotational grazing (PP), (c) crop-livestock integration in the cropping phase (CL-C), (d) soybean cropping under conventional tillage (CT), and (e) soybean cropping under no-till (NT).

and dry winters, according to the Köppen classification system (Alvares et al., 2013). The average annual precipitation and temperature are 1500 mm and 22 °C, respectively (Panachuki et al., 2006). The soil is classified as *Latossolo Vermelho Distrófico* (Ferralsol) with averages of 630, 215 and 155 g kg^{-1} clay, silt, and sand, respectively. The average slope of the experimental area is 0.03 m m^{-1}.

Experimental design and treatments

The experimental design was a randomized block with five treatments: crop rotation under conventional tillage (CT), crop rotation under no-till (NT), 2-year crop and 2-year livestock rotation in the livestock phase (CL-L), 2-year crop and 2-year livestock rotation in the cropping phase (CL-C), and permanent pasture (PP) (described in table 1). Soil fertilization (N-P-K ratio of 0–20–20, 300 kg ha^{-1}) was only performed during the soybean cropping phase in the crop-livestock integration system when sowing was carried out

Table 1. Description of the six treatments under different agricultural management

Treatments	Description
Crop rotation under conventional tillage (CT)	Soybean is cultivated during the summer and oats during the winter. Crops are sowed after conventional soil tillage using a heavy harrow and a leveling harrow. Soybean, cv. BRS 359 RR, was sowed following land contours with a row spacing of 0.45 m and seed rate ranging from 14 to 15 seeds m^{-1}.
Crop rotation under no-till (NT)	Soybean, cv. BRS 359 RR, and corn are cultivated during the summer. Soybean was sowed following land contours with a row spacing of 0.45 m and seed rate ranging from 14 to 15 seeds m^{-1}. During the fall-winter, wheat and oats are cultivated for grain production and turnip and oats for straw production (crop rotation sequence turnip – corn – oats – soybean – wheat – soybean).
Crop-livestock integration in the livestock phase (CL-L)	During the two-year cropping phase, soil fertilization was performed and soybean, cv. BRS 359 RR, and oats were sowed under no-till following land contours with a row spacing of 0.45 m and seed rate ranging from 14 to 15 seeds m^{-1}. During the two-year livestock phase, Nellore steers rotationally grazed a *Brachiaria decumbens* pasture based on the put-and-take stocking method (Mott and Lucas, 1952). The adjustment criterium consisted of a minimum forage availability of 7 kg of dry biomass per 100 kg day^{-1} of live animal weight (avg. w 300 kg). We carried out the analysis in the crop-livestock integration during the livestock phase.
Crop-livestock integration in the cropping phase (CL-C)	Two-year soybean/oats cultivation under no-till followed by two-year *Brachiaria decumbens* pasture under rotational and put-and-take stocking methods. Soil and agricultural management were identical to the above treatment (CL-L). We carried out the analysis during the soybean cropping phase.
Permanent pasture (PP)	*Brachiaria decumbens* pasture under rotational grazing and the put-and-take stocking method. The criterium of adjusting the stocking rate was a minimum forage availability of 7 kg of dry biomass per 100 kg day^{-1} of live animal weight (avg. w 300 kg). No fertilization was performed since the experiment implementation (1995).

in November 2014. The analyses were carried out in February 2015 during soybean phenological stage R5.1 (82 days from planting).

Analyses of soil physical properties

Undisturbed soil cores (100 cm^3) were collected from 0.00–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.40 m soil layers to determine soil bulk density (BD), total pore volume (TPV), macroporosity (Ma), microporosity (Mi), and penetration resistance (PR) with five replicates in duplicate, totaling 10 samples for each treatment. Particle density (PD) was obtained by using a volumetric flask, and TPV, Ma and Mi were obtained by using the tension table method (Teixeira et al., 2017). A bench penetrograph was used to obtain the soil resistance to penetration at the field capacity moisture tension.

Mean weighted diameter (MWD) and geometric mean diameter (GMD) indices were obtained by the dry sieving method (9.52- and 4.76-mm sieves) (Teixeira et al., 2017) using five replicates. Aggregate stability was determined by the wet sieving method (Teixeira et al., 2017), using a stack of sieves with diameters ranging from 0.105 to 2.00 mm and subjected to vertical shaking in a Yoder apparatus for 15 min (Yoder, 1936). The stability index was calculated according to Kemper and Rosenau (1986). Additionally, five replicates of soil samples from the topsoil (0.00–0.05 m) were collected to determine the organic carbon content (OC) by dry combustion and dry biomass (DBM).

Soil loss data

To assess interrill erosion and water infiltration in each treatment, we used a portable rainfall simulator (Figure 1f) with runoff plots of 0.7 m^2 bordered by 2 mm thick galvanized iron sheets (Alves Sobrinho et al., 2008). The runoff plots have a downward-slope side with a triangular form that directs the surface runoff to the collecting point. We analyzed the interrill erosion rates among the treatments due to the plot size used in this study. The equipment was calibrated to apply a rainfall intensity of 60 mm h^{-1} and a working pressure of 32 kPa. The rainfall simulations were carried out in February 2015 (rainy season) and were randomized blocks with five replicates for each treatment.

Before each simulation, we collected soil samples to compute the gravimetric soil water content following the method described in Teixeira et al. (2017). Prewetting to standardize the initial soil moisture (Cogo et al., 1984) was not performed since we observed a precipitation accumulation of 39.8 mm for 24 h before the simulation runs. Moreover, the kinetic energy was calculated using the software EnerChuva (Alves Sobrinho et al., 2001) considering the height of the spray nozzles, the working pressure, duration of the rainfall simulation, and the rainfall intensity applied.

Simulation runs lasted 60 min after surface runoff onset. We measured one-minute surface runoff volume at one-minute intervals using a graduated cylinder to compute water loss. In addition, surface runoff samples were collected every three minutes to compute soil loss. The samples were later placed in an oven at 60 °C long enough to ensure total evaporation. Thus, soil loss was calculated as the sediment load divided by the plot area (0.7 m^2).

Statistical analysis

We performed analysis of variance ($\alpha = 0.05$) and Tukey's test for mean separation when the analysis of variance showed significant changes ($p<0.05$).

RESULTS

Soil physical properties

The rotation cropping system under conventional tillage (CT) presented the lowest soil bulk density (BD) and the highest macroporosity (Ma) in the topsoil layer (0.00–0.05 m) compared with the other treatments (Table 2). Nevertheless, in the cropping system treatments, we observed that BD tended to increase as the soil depth increased, even in the NT system. On the other hand, we noted higher BD in the topsoil layer and lower BD in subsequent layers for livestock production, CL-L and PP treatments. Higher BD in the superficial layer (0.00–0.05 m) consequently led to higher soil resistance to penetration (PR) in PP. Nonetheless, the other treatment with livestock production (CL-L) did not present a similar PR, although we noted a similar BD in both treatments ($\alpha = 0.05$).

The organic carbon content (OC) was higher in the integrated crop-livestock systems and the permanent pasture. A higher OC is strongly related to more stable aggregates, geometric mean diameter (GMD) and mean weighted diameter (MWD). Compared with the other treatments, we found higher GMD and MWD in the PP treatment considering all soil layers. In addition, the crop-livestock systems CL-L and CL-C also presented good aggregation.

Soil erosion

The initial soil water content did not affect surface runoff or soil erosion since it did not differ among the agricultural land uses evaluated ($\alpha = 0.05$) (Table 3). The relationship

Table 2. Soil physical properties of Ferralsol under different agricultural management practices: Soil bulk density (BD), particle density (PD), mean weighted diameter (MWD), geometric mean diameter (GMD), soil penetration resistance (PR), organic carbon content (OC), macro- and microporosity (Ma and Mi), and the total pore volume (TPV)

Treatment	BD	PD	MWD	GMD	PR	OC	Ma	Mi	TPV
	$Mg\ m^{-3}$		mm		Mpa	$g\ kg^{-1}$	%		
0.00–0.05 m soil layer									
CT	1.22 **b**	2.92 **a**	1.74 **b**	2.60 **b**	0.91 **c**	31.72 **b**	19.58 **a**	34.61 **a**	54.19 **a**
NT	1.31 **ab**	2.90 **a**	1.40 **b**	2.12 **b**	1.77 **b**	33.74 **b**	15.86 **b**	35.00 **a**	50.86 **a**
CL-L	1.34 **a**	2.89 **a**	4.22 **a**	4.44 **a**	1.73 **b**	42.18 **a**	14.75 **b**	39.87 **a**	54.62 **a**
CL-C	1.30 **ab**	2.88 **a**	4.19 **a**	4.42 **a**	1.70 **b**	43.58 **a**	15.16 **b**	36.93 **a**	52.09 **a**
PP	1.33 **a**	2.88 **a**	3.91 **a**	4.23 **a**	2.26 **a**	41.72 **a**	10.77 **b**	42.85 **a**	53.62 **a**
0.05–0.10 m soil layer									
CT	1.38 **a**	2.90 **a**	2.65 **b**	3.34 **b**	1.35 **b**	29.32 **b**	17.80 **a**	38.20 **a**	55.58 **a**
NT	1.39 **a**	2.92 **a**	1.33 **c**	1.85 **c**	1.49 **b**	30.95 **b**	13.20 **b**	39.16 **a**	52.88 **a**
CL-L	1.40 **a**	2.87 **a**	3.11 **b**	3.70 **b**	1.56 **b**	32.58 **ab**	15.03 **a**	37.51 **a**	52.54 **a**
CL-C	1.36 **a**	2.89 **a**	3.28 **b**	3.99 **b**	1.66 **b**	30.06 **b**	14.93 **a**	36.11 **a**	51.04 **a**
PP	1.25 **b**	2.89 **a**	4.33 **a**	4.51 **a**	1.82 **a**	34.20 **a**	11.82 **c**	39.48 **a**	51.30 **a**
0.10–0.20 m soil layer									
CT	1.44 **a**	2.92 **a**	2.30 **b**	3.05 **bc**	3.02 **a**	26.57 **b**	6.98 **c**	44.04 **a**	51.02 **a**
NT	1.39 **b**	2.93 **a**	1.16 **c**	1.78 **d**	2.96 **a**	25.30 **b**	8.23 **b**	43.62 **a**	51.85 **a**
CL-L	1.36 **c**	2.90 **a**	2.12 **b**	2.88 **c**	1.71 **b**	32.34 **a**	10.35 **a**	42.51 **a**	52.86 **a**
CL-C	1.34 **c**	2.91 **a**	2.51 **b**	3.26 **b**	1.71 **b**	26.54 **ba**	9.80 **ab**	44.57 **a**	54.37 **a**
PP	1.27 **d**	2.90 **a**	3.83 **a**	4.19 **a**	1.38 **c**	28.97 **b**	11.77 **a**	40.98 **a**	52.75 **a**
0.20–0.40 m soil layer									
CT	1.41 **a**	2.91 **a**	1.35 **cd**	1.82 **cd**	1.52 **a**	23.19 **a**	7.53 **c**	44.23 **a**	51.76 **a**
NT	1.38 **a**	2.91 **a**	1.16 **d**	1.73 **d**	1.48 **b**	24.65 **a**	8.02 **c**	42.32 **a**	50.34 **a**
CL-L	1.32 **b**	2.90 **a**	1.65 **c**	2.39 **bc**	1.47 **b**	25.79 **a**	10.58 **b**	41,17 **a**	51.75 **a**
CL-C	1.31 **b**	2.89 **a**	2.10 **b**	2.83 **b**	1.48 **b**	24.50 **a**	11.14 **b**	41.41 **a**	52.55 **a**
PP	1.30 **b**	2.89 **a**	3.22 **a**	3.22 **a**	1.56 **a**	19.63 **b**	13.95 **a**	40.09 **a**	54.04 **a**

Different letter indicates different statistical groups ($\alpha = 0.05$); CT and NT are crop rotation systems under conventional tillage and no-till, respectively. CL-L is a crop-livestock integration system in the livestock phase and CL-C is in the cropping phase. PP is a Brachiaria decumbens permanent pasture under rotational grazing.

Table 3. Average values of dry plant mass (DBM), the kinetic energy of the rainfall simulations, and the initial water content

Treatments	DBM	Kinect energy	Initial water content
	$Mg\ ha^{-1}$	$kJ\ m^{-2}$	$kg\ kg^{-1}$
CT	8.43 **c**	1.99 **b**	0.19 **a**
NT	11.48 **bc**	5.36 **a**	0.19 **a**
CL-L	14.95 **a**	1.79 **c**	0.20 **a**
CL-C	12.08 **ab**	1.97 **b**	0.21 **a**
PP	3.90 **d**	1.73 **c**	0.21 **a**

Different letter indicates different statistical groups ($\alpha = 0.05$); CT and NT are crop rotation systems under conventional tillage and no-till, respectively. CL-L is a crop-livestock integration system in the livestock phase and CL-C is in the cropping phase. PP is a Brachiaria decumbens permanent pasture under rotational grazing.

between the simulated and natural rainfall kinetic energy was 96.6 % for all treatments. This implies that the rainfall simulations presented a satisfactory representation of natural rainfall conditions, as proposed by Meyer and McCune (1958). We also observed higher dry biomass (DBM) in the crop-livestock integration systems compared with CT and PP. Higher DBM is related to more vegetation cover, encouraging water infiltration and preventing soil erosion from the erosive power of rain. This corroborates the fact that we found reduced soil erosion in CL-L and CL-C despite the greater water loss in PP and soil loss in CT (Figure 2).

We noted higher surface runoff in PP with a water loss of approximately 36 % of the total precipitation amount. Nevertheless, soil loss in PP was similar to the results from NT, CL-L and CL-C, which presented lower water losses (Figure 2). Higher BD and lower Ma in the topsoil layer (0.00–0.05 m) contributed to the reduced water infiltration found in the permanent pasture treatment. Water and soil losses in CT were higher than those in the no-till (NT) treatment, which showed the lowest soil loss compared to the other treatments. No-till systems provide greater vegetation cover, protecting the soil from the erosive power of rain. In contrast, we observed less dry biomass (DBM) in CT than in NT, CL-L, and CL-C (Table 3). In addition, another factor that contributed to the higher soil erosion rates in CT was faster runoff generation than that in NT. The soil saturation in CT was eight times faster than that in NT despite the higher infiltration rate.

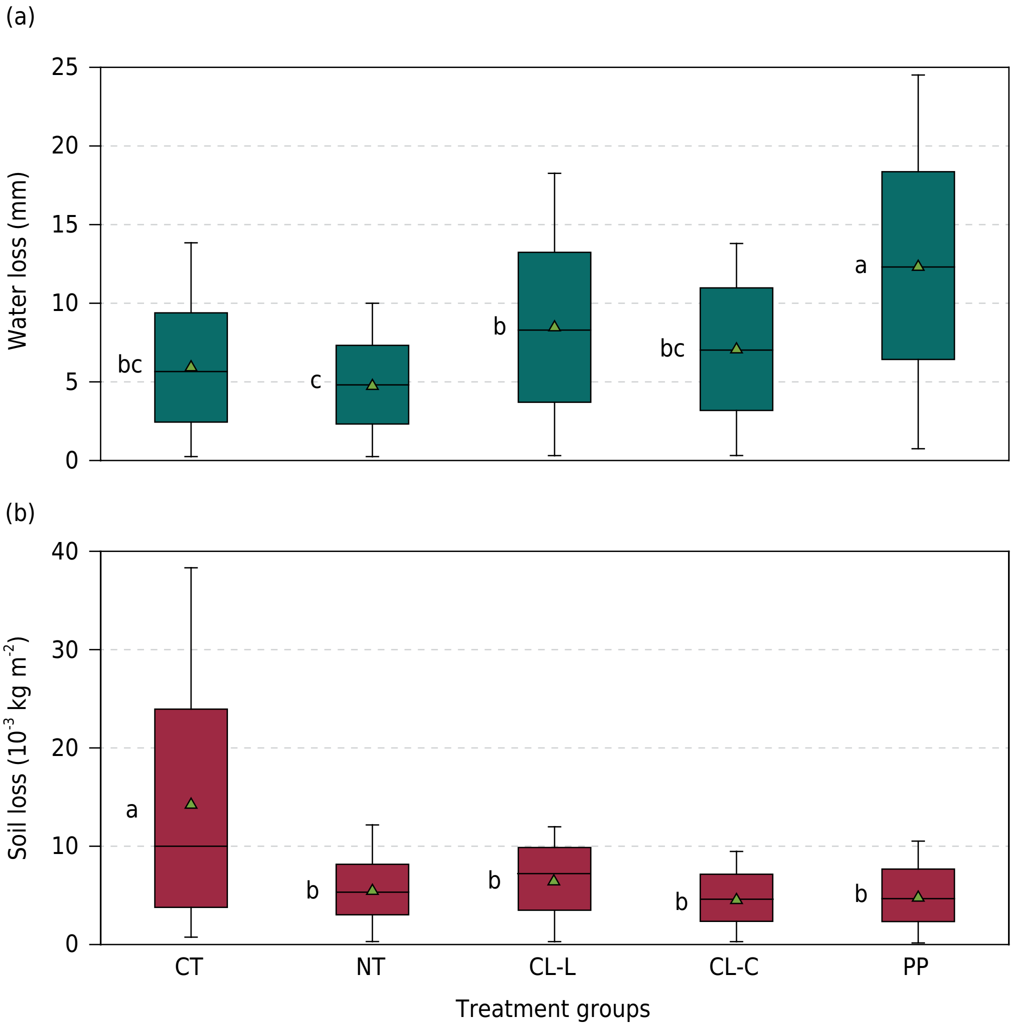

Figure 2. Boxplots of (a) water loss (mm) and (b) soil loss during the rainfall simulations on the agricultural land uses: soybean cropping under conventional tillage (CT), soybean cropping under no-till (NT), crop-livestock integration in the livestock phase (CL-L), crop-livestock integration in the cropping phase (CL-C), and Brachiaria decumbens permanent pasture under rotational grazing (PP). The 25th and 75th percentiles, the median with a line, and the mean with a triangle are shown; whiskers indicate the maximum and minimum values. Difference letters indicate different statistical groups by the Tukey test (α= 0.05).

DISCUSSION

Long-term effects on soil physical properties and soil erosion

The long-term effects of conventional tillage on soil physical properties were key for the observed higher soil erosion rates by water in CT. The soil bulk density was lower in the treatment under conventional tillage (CT) and lower in the treatment under no-till (NT). In NT, the long-term no-till practice may have negatively impacted some soil physical properties, such as increased BD and PR and decreased Ma, compared with CT. Subsoiling practices are a potential alternative to improve soil physical properties in croplands under no-till conditions. Periodic subsoiling can improve water infiltration in no-till systems by reducing BD (Panachuki et al., 2011). In CT, intense soil turning of the superficial soil layer due to leveling and digging with a harrow led to higher macroporosity (Ma) and lower soil resistance to penetration compared with NT, but it negatively impacted soil aggregate stability. This increased the soil vulnerability to soil erosion by water, especially when compared with the no-till treatment. Consequently, soil erosion rates in CT considerably increased as surface runoff started to occur due to greater soil shear stress. Panachuki et al. (2015) also found that the management practices adopted in conventional tillage systems made the soil more vulnerable to the erosive power of rain, against which vegetation cover plays an important role in protection. Furthermore, the residue cover in CT contributed to the highest soil loss rates (e.g., CT presented with a much lower DBM than NT, as shown in table 3).

We observed contrasting results in the treatment under permanent pasture, which showed higher surface runoff and a lower soil erosion rate. We did not find an improvement in water infiltration in the PP after long-term agricultural management was adopted since the study conducted by Panachuki et al. (2006) in the same study area. The grazing strategy adopted in PP may not have been adequate to avoid overgrazing, supported by the very low DBM shown in table 3. Although this treatment was managed as CL-L, a periodic rotation with cropping works as a service crop that is of paramount importance for improving agroecosystem resilience (Ogilvie et al., 2019). On the other hand, overgrazing leads to soil deterioration due to animal trampling, compacting the soil surface and causing soil sealing and crusting (e.g., higher BD in the topsoil layer and lower BD in subsequent layers for the treatments with livestock production, CL-L and PP). This leads to a decrease in water infiltration, as in other studies (Panachuki et al., 2006; Falcão et al., 2020) that, in turn, also causes an increase in soil erosion. In contrast, we noted good levels of stable soil aggregates in PP (MWD and GMD), contributing to soil erosion control. One of the strategies to overcome these negative impacts of permanent pastures on water infiltration is integrating a cropping phase with pasture periods, for which we observed promising results.

The crop-livestock systems (CL) presented reduced soil erosion and higher water infiltration even though BD increased since the preliminary study by Panachuki et al. (2006). In 2003, BD values ranged from 1.27 to 1.29 Mg m^{-3} (soil layer 00.0–0.20 m), while 12 years later, we observed values ranging from 1.34 to 1.40 Mg m^{-3} for CL-L in the same soil depth (0.00–0.20 m). Despite the increase in BD, the soil resistance to penetration (PR) in CL-L was not similar to that observed in PP ($\alpha = 0.05$). The organic carbon content (OC) may have played an important role in increasing water infiltration and reducing soil erosion despite the BD values found in CL-L. The greater biomass production contributed to maintaining high levels of OC—also found by Salton et al. (2011)—and high aggregate stability (MWD and GMD). Recent studies showed that pasture and cattle management have the potential to improve infiltration with rates similar to native vegetation, such as crop-livestock rotation and rotational stocking with an adaptive stocking rate (Sone et al., 2019, 2020), as in PP and CL systems. Those authors and Ernst et al. (2018) also reported that the rotation period between cropping and livestock production affects soil erosion and water infiltration rates, so it is key to adjust the rotation period to achieve adequate soil physical properties for environmental and agricultural sustainability.

Implications and future research opportunities

The experimental evidence found here after two decades of carrying out the studied agricultural land uses and management showed an opportunity for improving soil physical properties, positively affecting water infiltration and soil erosion control. In particular, crop-livestock rotation has the potential to halt global soil deterioration, increase food security and reduce the costs incurred because of soil erosion. Our findings show a reduction in surface runoff of approximately 30 % in the crop-livestock system in the livestock phase (CL-L) compared with permanent pasture (PP) and a reduction in soil erosion of approximately 60 % in the crop-livestock system in the cropping phase (CL-C) compared with conventional cropping (CT). Farmers can benefit from crop-livestock production, which can improve soil physical properties, as we observed in this study and has been corroborated by several others (Salton et al., 2014; Lemaire et al., 2019; Leterme et al., 2019). Nevertheless, politics will play a key role in encouraging the adoption of integration systems through sharing scientific knowledge, farmers' experiences, and economic implications, e.g., due to the lack of studies on the economic benefits of crop-livestock rotation, as pointed out by Franzluebbers and Gastal (2019).

This is a preliminary study on the long-term effects of five important agricultural systems in Brazil on some soil physical properties and soil erosion by water. Future research opportunities involve a deeper investigation of more soil properties and an implementation of larger soil erosion plots to account for not only splash and interrill erosion but also rill and gully erosion. Furthermore, a meticulous study of livestock management is fundamental to meet an adequate stocking rate depending on forage availability and, consequently, to minimize the negative impacts on soil physical properties and thus soil erosion by water. For instance, Sone et al. (2019) analyzed crop-livestock integration systems with different rotation periods and found that one-year cropping followed by three years of pasture considerably reduced water losses compared with four-year cropping followed by four-year livestock production. Despite the advantages of using small runoff plots, improving their accuracy will allow for larger-scale studies for more contextualized and general applications. Our study is a starting point for future and further research—e.g., using larger plots to investigate any scale influence—and it reveals the potential to minimize the agricultural footprint.

CONCLUSIONS

We investigated the impacts of long-term agricultural production under different management systems on soil physical properties and soil erosion. We found that even though the soil bulk density increased over the two decades of crop-livestock integration, this agricultural system improved aggregate stability and organic carbon incorporation into the soil, presenting higher water infiltration and reduced soil erosion. By comparing the treatments with cropping production, the integrated crop-livestock in the cropping phase (CL-C) reduced soil erosion by 60 % compared with cropping production under conventional tillage. On the other hand, livestock production integrated with cropping (CL-L) resulted in a reduction in water loss of 30 % when compared with the continuous pasture treatment (PP).

Considering the difficulties of finding studies of long-term periods after the implementation of crop-livestock integration systems, monitoring the effects of this agricultural production system over the years is an interesting research opportunity, which will help support decision-makers to adopt adequate measures to increase the synergism between the agricultural productions in each stage of integrated systems. Despite our study limitations, our findings reveal the potential for reducing soil erosion in agriculture, which is a major concern and causes economic loss. Furthermore, this study provides preliminary results and encourages future research showing that crop-livestock systems have the potential to minimize negative environmental impacts.

ACKNOWLEDGEMENTS

This study was supported by grants from the Fundação de Apoio ao Desenvolvimento do Ensino, Ciência e Tecnologia do Estado de Mato Grosso do Sul (FUNDECT), the Ministry of Science, Technology, and Innovation (MCTI) and the National Council for Scientific and Technological Development (CNPq) [grant number 441289/2017-7 and 306830/2017-5]. This study was also partly financed by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior — Brazil — CAPES [Finance Code 001 and CAPES PrInt). The authors acknowledge the Embrapa Western Agriculture, Dourados-MS, Brazil, for the partnership and providing us with the experimental area and the opportunity to carry out our research.

AUTHOR CONTRIBUTIONS

Conceptualization: Dorly Scariot Pavei (supporting) and Eloi Panachuki (lead).

Data curation: Dorly Scariot Pavei (lead).

Formal Analysis: Dorly Scariot Pavei (equal), Eloi Panachuki (lead), Julio Cesar Salton (equal), Jullian Souza Sone (equal), Teodorico Alves Sobrinho (supporting), Wander Cardoso Valim (supporting) and Paulo Tarso Sanches de Oliveira (supporting).

Investigation: Dorly Scariot Pavei (equal) and Eloi Panachuki (equal).

Methodology: Dorly Scariot Pavei (equal) and Eloi Panachuki (equal).

Validation: Dorly Scariot Pavei (lead).

Visualization: Jullian Souza Sone (lead).

Writing original draft: Dorly Scariot Pavei (lead).

Writing review and editing: Eloi Panachuki (equal), Julio Cesar Salton (supporting), Jullian Souza Sone (equal), Teodorico Alves Sobrinho (supporting), Wander Cardoso Valim (supporting) and Paulo Tarso Sanches de Oliveira (equal).

Funding acquisition: Eloi Panachuki (lead).

Project administration: Eloi Panachuki (lead).

Supervision: Eloi Panachuki (lead).

REFERENCES

Almeida WS, Panachuki E, Oliveira PTS, Silva Menezes R, Sobrinho TA, Carvalho DF. Effect of soil tillage and vegetal cover on soil water infiltration. Soil Till Res. 2018;175:130-8. https://doi.org/10.1016/j.still.2017.07.009

Alvares CA, Stape JL, Sentelhas PC, de Moraes Gonçalves JL, Sparovek G. Köppen’s climate classification map for Brazil. Meteorol Z. 2013;22:711-28. https://doi.org/10.1127/0941-2948/2013/0507

Alves Sobrinho T, Carvalho DF, Aquino RM, Montebeller CA. Programa computacional para a definição de parâmetros hidráulicos utilizados na determinação da energia cinética da chuva simulada em infiltrômetros de aspersão. Engenharia Rural. 2001;12:28-35.

Alves Sobrinho T, Gómez-Macpherson H, Gómez JA. A portable integrated rainfall and overland flow simulator. Soil Use Manage. 2008;24:163-70. https://doi.org/10.1111/j.1475-2743.2008.00150.x

Cade-Menun BJ, Bainard LD, LaForge K, Schellenberg M, Houston B, Hamel C. Long-term agricultural land use affects chemical and physical properties of soils from southwest Saskatchewan. Can J Soil Sci. 2017;97:650-66. https://doi.org/10.1139/cjss-2016-0153

Cogo NP, Moldenhauer WC, Foster GR. Soil loss reductions from conservation tillage practices. Soil Sci Soc Am J. 1984;48:368-73. https://doi.org/10.2136/sssaj1984.03615995004800020029x

Dechen SCF, Telles TS, Guimarães MF, Maria IC. Perdas e custos associados à erosão hídrica em função de taxas de cobertura do solo. Bragantia. 2015;74:224-33. https://doi.org/10.1590/1678-4499.0363.

Dekemati I, Simon B, Vinogradov S, Birkás M. The effects of various tillage treatments on soil physical properties, earthworm abundance and crop yield in Hungary. Soil Till Res. 2019;194:104334. https://doi.org/10.1016/j.still.2019.104334

Ernst OR, Dogliotti S, Cadenazzi M, Kemanian AR. Shifting crop-pasture rotations to no-till annual cropping reduces soil quality and wheat yield. Field Crop Res. 2018;217:180-7. https://doi.org/10.1016/j.fcr.2017.11.014

Falcão KS, Panachuki E, Monteiro FN, Menezes RS, Rodrigues DBB, Sone JS, Oliveira PTS. Surface runoff and soil erosion in a natural regeneration area of the Brazilian Cerrado. Int Soil Water Conserv Res. 2020;8:124-30. https://doi.org/10.1016/j.iswcr.2020.04.004

Franzluebbers AJ, Gastal F. Building agricultural resilience with conservation pasture-crop rotations. In: Lemaire G, Carvalho PCF, Recous S. Agroecosystem diversity - Reconciling contemporary agriculture and environmental quality. Cambridge: Academic Press; 2019. p. 109-21. https://doi.org/10.1016/B978-0-12-811050-8.00007-8

Jose S. Agroforestry for ecosystem services and environmental benefits: an overview. Agroforestry Syst. 2009;76:1-10. https://doi.org/10.1007/s10457-009-9229-7

Kemper WD, Rosenau RC. Aggregate stability and size distribution. In: Kluter A, editor. Methods of soil analysis: Part 1 - Physical and mineralogical methods. 2nd ed. Madison: Soil Science Society of America; 1986. p. 1149-78.

Lemaire G, Giroud B, Bathily B, Lecomte P, Corniaux C. Toward integrated crop-livestock systems in West Africa. In: Lemaire G, Carvalho PCF, Recous S. Agroecosystem diversity - Reconciling contemporary agriculture and environmental quality. Cambridge: Academic Press; 2019. p. 275-85. https://doi.org/10.1016/B978-0-12-811050-8.00017-0

Leterme P, Nesme T, Regan J, Korevaar H. Environmental benefits of farm- and district-scale crop-livestock integration. In: Lemaire G, Carvalho PCF, Recous S. Agroecosystem diversity - Reconciling contemporary agriculture and environmental quality. Cambridge: Academic Press; 2019. p. 335-49. https://doi.org/10.1016/B978-0-12-811050-8.00021-2

Meyer LD, McCune DL. Rainfall simulator for field studies of run-off and soil erosion. Agr Eng. 1958;39:644-8. https://doi.org/10.1016/0021-8634(77)90091-9

Murphy B, Fogarty P. Application of the soil security concept to two contrasting soil landscape systems - Implications for soil capability and sustainable land management. Sustainability. 2019;11:5706. https://doi.org/10.3390/su11205706

Ogilvie CM, Deen W, Martin RC. Service crop management to maximize crop water supply and improve agroecosystem resilience : A review. J Soil Water Conserv. 2019;74:389-404. https://doi.org/10.2489/jswc.74.4.389

Panachuki E, Alves Sobrinho T, Vitorino ACT, Carvalho DF, Urchei MA. Parâmetros físicos do solo e erosão hídrica sob chuva simulada, em área de integração agricultura-pecuária. Rev Bras Eng Agr Amb. 2006;10:261-8. https://doi.org/10.1590/S1415-43662006000200003

Panachuki E, Bertol I, Alves Sobrinho T, Oliveira PTS, Rodrigues DBB. Perdas de solo e de água e infiltração de água em Latossolo vermelho sob sistemas de manejo. Rev Bras Cienc Solo. 2011;35:1777-85. https://doi.org/10.1590/S0100-06832011000500032

Panachuki E, Santos MAN, Pavei DS, Alves Sobrinho T, Montanari R. Soil and water loss in Ultisol of the Cerrado-Pantanal Ecotone under different management systems. Afr J Agr Res. 2015;10:926-32. https://doi.org/10.5897/AJAR2014.8908

Pham TG, Nguyen HT, Kappas M. Assessment of soil quality indicators under different agricultural land uses and topographic aspects in Central Vietnam. Int Soil Water Conserv Res. 2018;6:280-8. https://doi.org/10.1016/j.iswcr.2018.08.001

Salton JC, Mercante FM, Tomazi M, Zanatta JA, Concenço G, Silva WM, Retore M. Integrated crop-livestock system in tropical Brazil: Toward a sustainable production system. Agr Ecosyst Environ. 2014;190:70-9. https://doi.org/10.1016/j.agee.2013.09.023

Salton JC, Mielniczuk J, Bayer C, Fabrício C, Cláudio M, Macedo M, Broch DL. Teor e dinâmica do carbono no solo em sistemas de integração lavoura-pecuária. Pesq Agropec Bras. 2011;46:1349-56. https://doi.org/10.1590/S0100-204X2011001000031

Sartori M, Philippidis G, Ferrari E, Borrelli P, Lugato E, Montanarella L, Panagos P. A linkage between the biophysical and the economic: Assessing the global market impacts of soil erosion. Land Use Policy. 2019;86:299-312. https://doi.org/10.1016/j.landusepol.2019.05.014

Sone JS, Oliveira PTS, Euclides VPB, Montagner DB, Araujo AR, Zamboni PAP, Vieira NOM, Carvalho GA, Sobrinho TA. Effects of nitrogen fertilisation and stocking rates on soil erosion and water infiltration in a Brazilian Cerrado farm. Agr Ecosyst Environ. 2020;304:107159. https://doi.org/10.1016/j.agee.2020.107159

Sone JS, Oliveira PTS, Zamboni PAP, Motta Vieira NOM, Carvalho GA, Macedo MCM, Araujo AR, Montagner DB, Alves Sobrinho T. Effects of long-term crop-livestock-forestry systems on soil erosion and water infiltration in a Brazilian Cerrado site. Sustainability. 2019;11:5339. https://doi.org/10.3390/su11195339

Teixeira PC, Donagemma GK, Fontana A, Teixeira WG. Manual de métodos de análise de solo. 3. ed. rev e ampl. Brasília, DF: Embrapa; 2017.

Vrese P, Stacke T, Hagemann S. Exploring the biogeophysical limits of global food production under different climate change scenarios. Earth Syst Dynam. 2018;9:393-412. https://doi.org/10.5194/esd-9-393-2018

Yoder RE. A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses. Agron J. 1936;28:337. https://doi.org/10.2134/agronj1936.00021962002800050001x

Zajícová K, Chuman T. Effect of land use on soil chemical properties after 190 years of forest to agricultural land conversion. Soil Water Res. 2019;14:121-31. https://doi.org/10.17221/5/2018-SWR