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ORIGINAL ARTICLE

Short-term effect of a crop-livestock-forestry system on soil, water and nutrient loss in the Cerrado-Amazon ecotone

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ABSTRACT

Soil, water, and nutrient loss by water erosion are among the main factors leading to land degradation, decreasing soil productivity and the provision of ecosystem services. The Cerrado-Amazon ecotone in western Brazil has suffered rapid land-use cover changes with impacts on soil erosion and land degradation. Despite the importance of the region for Brazilian agriculture and environmental conservation, studies on soil, water, and nutrient loss are still scarce. We tested integrated crop-livestock-forestry (ICLF) as a sustainable agriculture management system for the Cerrado-Amazon ecotone region. A field experiment was established in the north of Mato Grosso state to quantify total soil, water, carbon and nitrogen loss during the rainy season in 2012-2013 in plots of integrated crop-forestry (ICF), pasture (PAST), eucalyptus plantation (EUC), no-tillage crop succession (CS) and bare soil (BS). Total soil, water, carbon and nitrogen losses in BS were, on average, 96.7% higher than in ICF, EUC, PAST, and CS. ICF had significantly lower water loss than CS, EUC and PAST. Total loss of carbon (4.3 - 428.2 kg ha^{-1}) and nitrogen (0.3 - 29.2 kg ha^{-1}) differed significantly among treatments. The production systems with tree components (EUC and ICF) and PAST showed reduced soil and nutrients loss compared to CS. Our results demonstrated that ICLF can avoid soil quality loss and thus improve agriculture sustainability in the Cerrado-Amazon ecotone.

KEYWORDS: water erosion, soil function, sustainability, integrated production systems

Efeito da integração lavoura-pecuária-floresta em fase inicial sobre as perdas de solo, água e nutrientes no ecótono Cerrado-Amazônia

RESUMO

A erosão hídrica é um dos principais fatores da degradação dos solos, impactando seu potencial produtivo e capacidade de provisão de serviços ecossistêmicos. O ecótono Cerrado-Amazônia, no norte de Mato Grosso, Brasil, tem sofrido intensas modificações em seu uso e cobertura com impacto na erosão e degradação do solo. Apesar da importância ambiental e agropecuária da região, estudos sobre as perdas de água, solo e nutrientes são escassos. Neste trabalho, testamos a utilidade da integração lavoura-pecuária-floresta (ICLF) para a produção agrícola sustentável no ecótono Cerrado-Amazônia. Foi implantado um experimento de campo no norte de Mato Grosso para quantificar as perdas de solo, água, carbono e nitrogênio durante o período chuvoso de 2012-2013 em parcelas de integração lavoura-floresta (ICF), pastagem (PAST), plantação de eucalipto (EUC), plantio direto com sucessão de culturas (CS) e solo descoberto (BS). As perdas totais de água, solo, carbono e nitrogênio foram, em média, 96,7% maiores em BS, quando comparadas a ICF, EUC, PAST e CS. As perdas de água e solo foram significativamente menores na ICF comparado a CS. As perdas totais de carbono (4.3 - 428.2 kg ha^{-1}) e nitrogênio (1.05 - 10.4 kg ha^{-1}) diferiram significativamente. Os sistemas com um componente arbóreo (EUC e ICF) e PAST tiveram menores perdas de solo e nutrientes em comparação com CS. Nossos resultados demonstraram que ICLF pode evitar a perda de qualidade de solo, melhorando a sustentabilidade da agricultura no ecótono Cerrado-Amazônia.

PALAVRAS-CHAVE: erosão hídrica, funções do solo, sustentabilidade, sistemas integrados de produção

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INTRODUCTION

Accelerated land-use and land-cover change has dramatically impacted soil erosion, leading to severe losses of soil, water and nutrients and corresponding loss of productivity and soil health of soils (Sobral *et al*. 2015; Dollinger and Jose 2018). Soil degradation due to erosion is a serious problem and needs to be addressed in the 21st century, notably in developing countries of the tropics and subtropics (Lal 2001) where erosion is often increased by factors, such as the removal of forest cover, intense rainfall, high erodibility of geologically old and weathered soils and inappropriate soil management (Wantzen and Mol 2013).

There is a growing concern on how to reduce the impact of agricultural production systems on natural environments while, at the same time, assuring food security (FAO 2009; 2014). In this context, intensive but sustainable production systems such as integrated crop-livestock forestry (ICLF) can reduce environmental degradation while maintaining or increasing crop productivity (FAO 2010). The ICLF is a sustainable production strategy that integrates crops, livestock, and forestry in the same area through intercropping cultivation, cultivation in succession, and crop rotation, aiming at synergistic effects among the components of the agroecosystem (Balbino *et al.* 2011; De Moraes *et al.* 2014). The system is based on diversified animal and plant production designed to optimize biological cycles and residue input. ICLF contributes to the recovery of degraded areas, as well as to the maintenance and restoration of vegetation cover and the adoption of good agricultural practices (GAP), including no-tillage soil management (FAO 2010; Balbino *et al.* 2011). The production strategy of ICLF also seeks to improve the human social condition in rural areas, through promotion and generation of jobs and incomes, conforming production units to environmental legislation and the appreciation of environmental services offered by agroecosystems (Balbino *et al*. 2011).

Despite the potential of ICLF for agricultural intensification and sustainability, studies on the quantification of the agricultural, social and environmental dimensions of ICLF systems are still scarce. Soil erosion and further effects on soil quality are expected under no-till and ICLF systems in the medium and long-term. However, soil and water loss may occur in short periods after ICLF establishment (Rieger *et al*. 2016; Zolin *et al*. 2016), which is more critical due to lower soil cover.

In the Brazilian Amazon, soil erosion could dramatically reduce the resilience of disturbed tropical forests, favoring the substitution by alternative vegetation forms that are persistently vulnerable to erosion (Flores *et al.* 2019). The north of Mato Grosso state, in the southern Brazilian Amazon, has experienced significant changes in land use and cover, which can directly impact soil and water conservation, as well as the hydrological regime of the region (Zaiatz *et al.* 2018; Oliveira *et al.* 2019). In this context, ICLF systems can play a critical role in coupling sustainable agriculture with minimizing negative impacts on the environment in the agricultural frontier of the southern Brazilian Amazon (the ecotone between the Amazon and the Cerrado savanna biomes). Furthermore, policies intended to provide preferential credit lines to finance investments into the low-carbon economy are a major factor driving this region of Brazil to adopt sustainable agricultural practices such as ICLF (Carauta *et al*. 2018; Schaldach *et al*. 2018).

Although there are multiple studies evaluating the impact of agricultural practices (e.g. tillage and no-tillage systems, cover crops, soil management) on water erosion in Brazil (Beutler *et al.* 2003; Silva *et al.* 2005; Barbosa *et al.* 2010; Merten and Minella 2013), data on the ability of ICLF to reduce soil, water and nutrient loss relative to other systems, especially in regions of accelerated agricultural expansion, are still lacking. Also, little information exists on the impact of soil, water and nutrient loss in ICLF systems in the agricultural frontier of the southern Brazilian Amazon, which is one of the most important for soy and corn, as well as livestock production in Brazil.

Therefore we aimed to assess the suitability of ICLF for sustainable agriculture management in the Cerrado-Amazon ecotone. We established a field experiment to compare soil, water and nutrient loss in ICLF relative to other land uses. Our specific goals were: (a) to evaluate if ICLF is more efficient than other conservationist systems to reduce soil, water, carbon and nitrogen loss in the short-term; and (b) to determine the magnitude of the variability in carbon and nitrogen content in eroded sediment from ICLF-covered systems and bare soil.

MATERIAL AND METHODS

Site description

The field experiment was conducted at the experimental farm (11°51’50”S, 55°37’39”W, 364 masl) of Embrapa Agrossilvipastoril, in the municipality of Sinop, in the state of Mato Grosso. The climate of the region is of Aw (tropical with dry winter) type, according to the Köppen classification, with average annual temperature of 24.7 °C and rainfall of 1974 mm, concentrated from October/November to March/April (Souza *et al*. 2013) (Figure 1). The soil of the experimental site is classified as dystrophic Red Yellow Latosol (Oxisol) (Viana *et al*. 2015), a Typic Dystrophic Hapludox (Soil Survey Staff 2014). The soil is developed on a gently rolling landscape, on sand feldspar sediments dominated by kaolinite and gibbsite and is characterized by a clayey texture with a moderate A (0.00-0.20 m) horizon and a deep B (0.20-1.00 m) horizon. Texture of the surface horizon is determined by 32% sand, 12% silt and 56% clay (Viana et al. 2015).

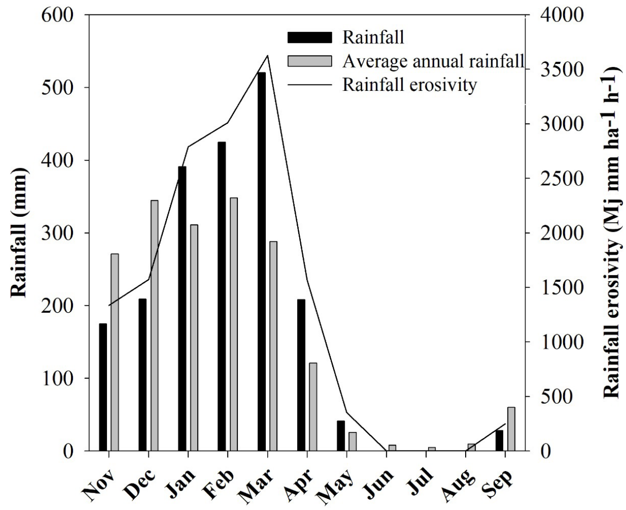

Figure 1. Average annual rainfall, monthly rainfall and rainfall erosivity from November 2012 to September 2013 at the experimental farm of Embrapa Agrossilvipastoril, Sinop, Mato Grosso state, Brazil.

During the 2007/2008 and 2008/2009 growing seasons, soybean (*Glycine max L.*) and cotton (*Gossypium hirsutum L.)* were planted in succession in the experimental area (approximately 100 ha), and in the 2009/2010 and 2010/2011 seasons, the land was left fallow. The experiment was implemented in October 2011, with soybean sowing, and the transplanting of eucalyptus seedlings occurred in November 2011.

Experimental design

Soil, water and nutrient loss was monitored in five treatments: (1) integrated crop-forestry system (ICF), consisting of eucalyptus (*Eucalyptus urograndis* clone H13 (obtained from a commercial nursery with standard size for expedition ranging from 20-30 cm) as the tree component (three rows with 3.5 x 3 m spacing and 30 m between rows), and soybean followed by corn (*Zea mays* L.), intercropped with *Urochloa brizantha* cv. Marandu under a no-tillage system as the crop component (in the 30-m spaces between eucalyptus rows); (2) *Urochloa brizantha* cv. Marandu pasture (PAST); (3) eucalyptus (*E. urograndis* clone H13) plantation (EUC) with 3.5 x 3 m spacing ; (4) crop succession of soybean followed by corn, intercropped with *U. brizantha* in no-tillage system (CS); and (5) bare soil (BS). Single systems (PAST, EUC, and CS) were evaluated in 1-ha experimental plots, while for integrated systems (ICF and CS), 2-ha plots were used. For each production system, as well as for BS, one sub-plot for runoff measurement was used (Figure 2). The fertilizers applied during the experiment are listed in Table 1.

Corn and soybean were sown at row spacing of 0.45 m, perpendicular to the slope. Pasture was also sown at row spacing of 0.45 m, with 4 kg ha^{-1} of viable seeds. Pasture was managed without grazing until December 2012, when it was harvested to simulate grazing. Eucalyptus seedlings were planted in furrows (with a furrower) at 3.5 x 3 m spacing. Weed control in the EUC treatment was performed in early March 2013 by mechanical mowing in the plant interrow. The eucalyptus trees had a mean height of 3.5 m in November 2012 and 6 m in April 2013.

In November 2011, after subsoiling to alleviate compaction (chisel plowing to 40 cm depth) and a light soil-harrow operation, we started the experiment, and in October 2012 we started monitoring soil, water, and nutrients loss. Measurements of runoff and soil erosion were made from sub-plots of 132 m^2, based on the standard plot of the USLE model (Wischmeier and Smith 1978). One sub-plot with a slope of approximately 1.5% was established in each treatment (Figure 2). The sub-plot was enclosed at the top and sides by 6 x 22 m galvanized sheets inserted in the soil to a depth of approximately 0.15 m. The length of the sub-plot was parallel to the slope of the terrain. Runoff-collection flumes were

Table 1. Characteristics of the treatments estabilshed in experimental plots of different management systems to evaluated soil, water and nutrient loss in Sinop, Mato Grosso state, Brazil. Fertilizer application occurred along the evaluation period (crop year 2012/2013), except for pasture, where application occurred during establishment (crop year 2011/12).

Treatment	Acronym	Tree component	Grain and pasture component	Fertilization
Pasture	PAST	-	*Urochloa brizantha*	12, 105 and 56 kg ha^{-1} N, P_2O_5, and K_2O respectively
Integrated crop-forestry system	ICF	*Eucalyptus urograndis* (H13)	soybean, corn, *Urochloa brizantha*	0, 70 and 70 kg ha^{-1} N, P_2O_5, and K_2O respectively in sowing (October 15, 2012) for soybean. 12, 90 and 48 kg ha^{-1} N, P_2O_5, and K_2O respectively in sowing (February 19, 2013) + 132 kg ha^{-1} N in topdressing for corn. 80, 20 and 80 kg ha^{-1} N, P_2O_5, and K_2O respectively for the tree component.
Eucalyptus plantation	EUC	*Eucalyptus urograndis* (H13)	-	80, 20 and 80 kg ha^{-1} N, P2O5, and K2O, applied mechanically in a continuous fillet on the ground.
No-tillage system with crop succession	CS	-	soybean, corn, *Urochloa brizantha*	0, 70 and 70 kg ha^{-1} N, P_2O_5, and K_2O respectively in sowing (October 15, 2012) for soybean. 12, 90 and 48 kg ha^{-1} N, P_2O_5, and K_2O respectively in sowing (February 19, 2013) + 132 kg ha^{-1} N in topdressing for corn.
Bare soil.	BS	-	-	No nutrient input

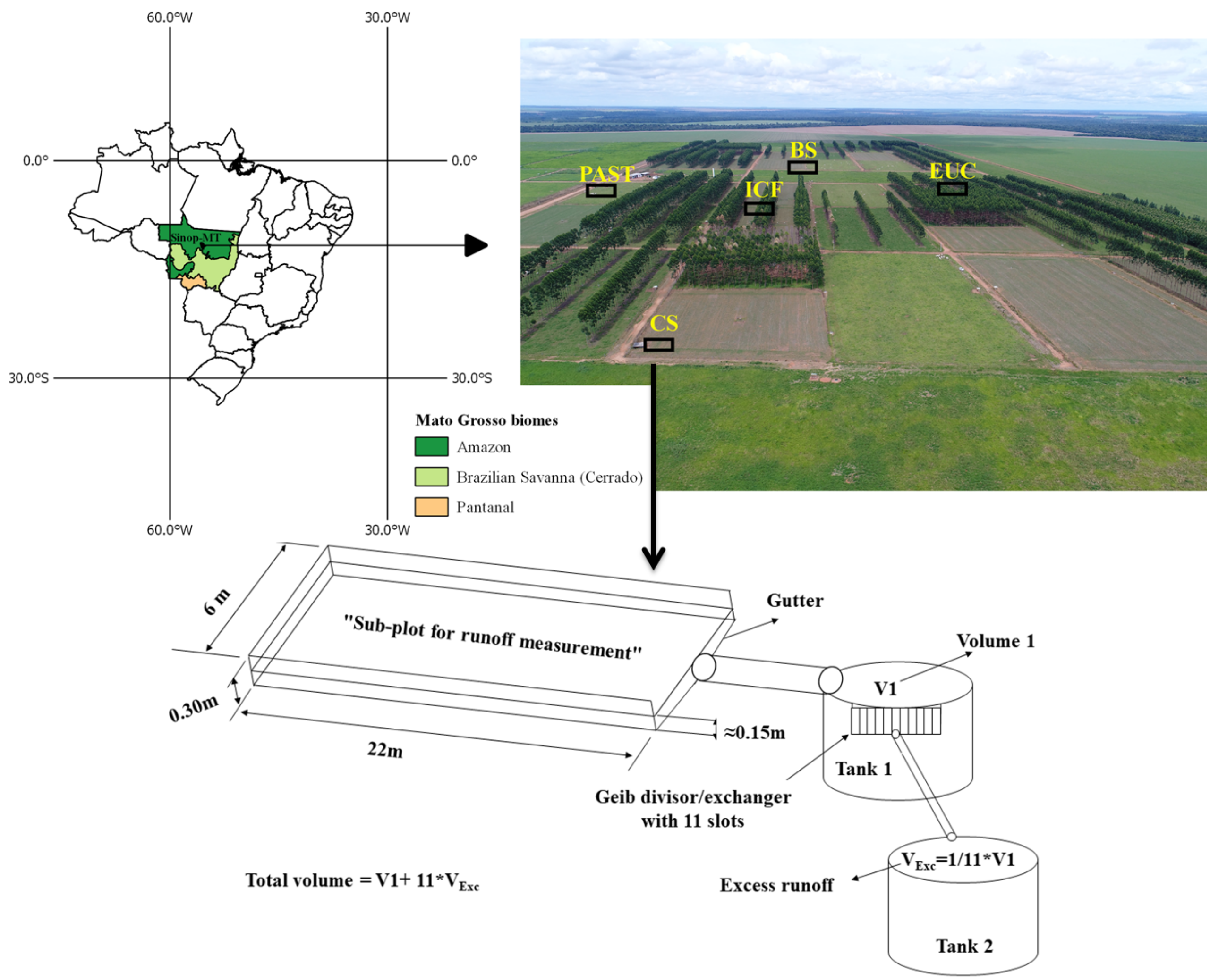

Figure 2. Location of the study area in Mato Grosso state, Brazil and an aerial image of the study area in the experimental farm of Embrapa Agrossilvipastoril, municipality of Sinop, showing the experimental plots of different production systems for the evaluation of short-term soil, water and nutrient loss. Below is a schematic drawing of the water and sediment collector system installed in each experimental plot (black rectangles on the aerial image) for the measurement of runoff and soil erosion. ICF – integrated crop-forestry system; PAST – pasture system; EUC – eucalyptus plantation; CS – no-tillage system with crop succession; BS – bare soil. Credit: Gabriel Rezende Faria (aerial image) and the authors (drawing).

installed at the lower end, where the surface runoff flow was directed via PVC pipes into two 1,000-L collection tanks. A Geib divisor with 11 slots was installed between the tanks to conduct 1/11 of the excess runoff from the first into the second tank.

Data collection and laboratory analyses

Water volume and eroded sediment samples were collected to determine carbon (C) and nitrogen (N) content immediately after rainfall events that caused surface runoff during the rainy season, from November 2012 to April 2013 (30 events).

In order to quantify soil and water loss, runoff and sediment samples were collected from the water tanks. Coarse sediments were held in a 50-L cotton bag installed in the first tank. After the runoff present in the tanks was homogenized, aliquots were collected and filtered with quantitative filter paper to determine the suspended sediments. The filtered material and coarse sediments were dried in an oven at 60°C for dry matter determination (Rieger *et al.* 2016).

Sediment samples used to determine C and N content were air dried, ground by a mill to pass through a 0.106 mm sieve and analyzed by CHNS analyzer (Vario Macro Elementar Analysensysteme, Hanau, Germany). We considered only sediment-associated C and N loss, thus, C and N loss in solution associated with surface runoff was not considered. As no inorganic C was present in the samples, total C corresponded to total organic C content.

Sediments from each runoff event were analyzed for C and N content by the product between the nutrient content and the soil mass and then pooled to determine the monthly loss. Prior to the rainfall season, 20 soil samples were randomly collected from the 0 to 0.05 m layer in each experimental plot. The samples were pooled into one composite sample per plot to quantify the average content of C and N present in the surface soil layer. The pre-rainfall content and the content in the eroded sediment were used to calculate the Enrichment Ratio (ER) by dividing the average nutrient content from the eroded soil (average of the 30 events) by the average nutrient content in the pre-rainfall soil (Hernani *et al*. 1999; Silva *et al*. 2005). An ER >1 implies increase the and ER < 1 implies depletion of the nutrient content in the eroded sediment (Hernani *et al*. 1999).

Statistical analysis

Each rainfall event was considered a replication for soil, water, and nutrient loss in each treatment. The data series of water, soil, and nutrient loss for 30 rainfall events were tested for normality and homogeneity of variance with the Shapiro-Wilks and Levene tests, respectively. As the variables did not follow a normal distribution and were not *homoscedastic*, the data were compared among treatments with Mann-Whitney U-tests (for independent groups) at a significance level of 5%. The relationship of the overall means of soil loss with ER values per treatment, and of the monthly values of rainfall with C and N loss, was analyzed using simple linear regression.

RESULTS

Soil and water loss

Soil and water loss differed significantly among the treatments and ranged from 0.156 to 16.98 Mg ha^{-1} and 34 to 675 mm, respectively. The highest values of soil and water loss were observed in BS, respectively 16.98 Mg ha^{-1} and 675 mm. Among the production systems, water loss was significantly lower in ICF (34.52 mm). Soil loss was significantly lower in ICF (0.238 Mg ha^{-1}), EUC (0.194 Mg ha^{-1}) and PAST (0.156 Mg ha^{-1}) compared to CS (0.856 Mg ha^{-1}) (Table 2).

Table 2. Monthly and total soil, water, carbon and nitrogen loss for 30 rainfall events during the rainy season from November 2012 to April 2013 in experimental plots of different management systems in Sinop, Mato Grosso state, Brazil. Monthly values are the sum of values of all rainfall events in the month.

Month	Number of rainfall events	Treatments				
		Pasture (PAST)	Integrated crop-forestry system (ICF)	Eucalyptus plantation (EUC)	No-tillage system with crop succession (CS)	Bare soil (BS)
				Soil loss (Mg ha^{-1})		
Nov	4	0.012	0.051	0.100	0.096	0.898
Dec	4	0.027	0.098	0.019	0.104	2.387
Jan	6	0.041	0.009	0.039	0.076	4.280
Feb	7	0.071	0.062	0.013	0.392	5.569
Mar	6	0.003	0.018	0.023	0.159	3.036
Apr	3	0.001	0.000	0.000	0.028	0.809
Total	30	0.156a	0.238a	0.194a	0.856b	16.980c
				Water loss (mm)		
Nov	4	3.519	0.996	2.333	1.480	26.515
Dec	4	10.084	2.689	9.708	7.352	50.652
Jan	6	8.709	6.924	10.229	8.538	90.074
Feb	7	15.768	13.525	15.245	14.296	206.937
Mar	6	7.846	9.322	18.105	14.947	234.348
Apr	3	1.622	1.068	1.798	1.486	66.786
Total	30	47.549b	34.524 a	57.419b	48.100b	675.313c
				Nutrient loss (kg ha^{-1})		
				Nitrogen		
Total	30	0.27a	0.36a	0.46a	1.34b	29.23c
				Carbon		
Total	30	4.27a	4.82a	6.81a	20.48b	428.17c

Different lowercase letters indicate significant differences between treatments according to the Mann-Whitney U test.

C and N content in the eroded sediment

The C and N content in the eroded sediment ranged from 15.24 to 137 g kg^{-1} and 1.05 to 10.4 g kg^{-1}, respectively. BS, CS and ICF had similar median values for C and N content in the eroded sediments, and lower variability than PAST and EUC (Figure 3). Contents in PAST and EUC were more variable and had higher median values (Figure 3), resulting in a greater range of values of C and N in the sediments.

Monthly and accumulated C and N loss

C and N loss in BS increased significantly between November and February, the period of intense rainfall (Figures 4, 5) and showed a strongly positive relationship with monthly rainfall (r^2 = 0.94 and r^2 = 0.95, respectively). No relationship was found between monthly rainfall and C and N loss for CS, EUC and ICF treatments.

Similarly, C and N loss in PAST also increased until February, while the other treatments did not follow the same trend, with highest values for C and N loss in CS in February, probably due to the soybean harvest (on 06 Feb 2013) and sowing of corn (on 19 Feb 2013).

Over the entire evaluation period (November 2012 to April 2013), total loss of C and N in BS (428 kg ha^{-1} C and 29 kg ha^{-1} N) was significantly higher than in ICF (4.8 kg ha^{-1} C and 0.35 kg ha^{-1} N), EUC (6.8 kg ha^{-1} C and 0.46 kg ha^{-1} N), PAST (4.3 kg ha^{-1} C and 0.27 kg ha^{-1} N) and CS (20.5 kg ha^{-1} C and 1.34 kg ha^{-1} N). There was no significant difference in C and N loss among ICF, EUC and PAST, however, losses were significantly higher in CS (Table 2).

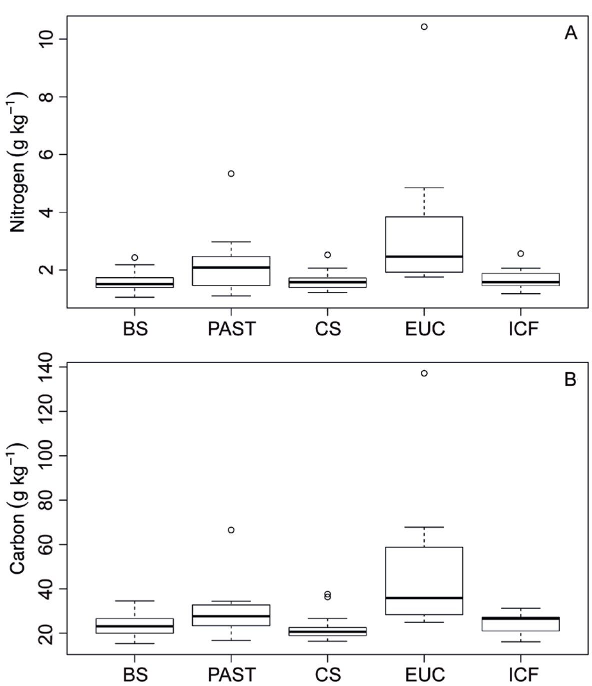

Figure 3. Carbon, C (A) and nitrogen, N (B) contents in the eroded sediment collected from experimental plots of different production systems in Sinop, MatoGrosso state, Brazil, from November 2012 to April 2013. PAST – pasture; ICF – integrated crop-forestry system; EUC – eucalyptus plantation; CS – no-tillage system with crop succession; and BS - bare soil. In the box-plot, the central line indicates the median, the box the 25-75% quartiles, and the bars the range. Circles indicate outlier values.

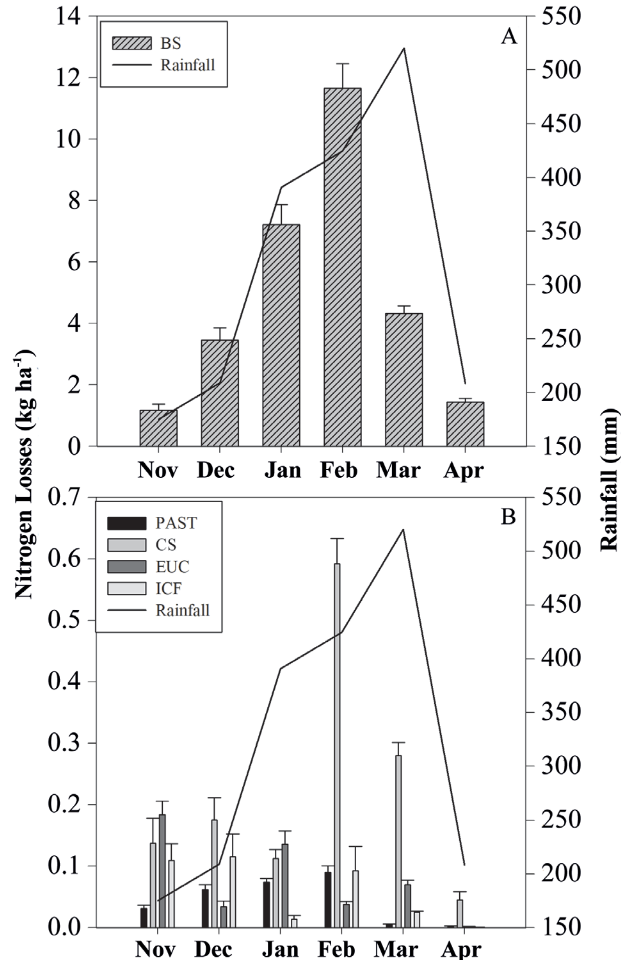

Figure 4. Monthly averages of rainfall and nitrogen (N) loss in the eroded sediment from experimental plots of different management systems in Sinop, Mato Grosso state, Brazil. A – BS = bare soil; B – PAST = pasture; ICF = integrated crop-forestry system; EUC = eucalyptus plantation; CS = no-tillage system with crop succession. Columns are the mean and bars the standard error.

Enrichment ratio

With the exception of EUC and PAST, eroded sediments were not enriched with C and N (Table 3). ER was higher in EUC and PAST. In EUC, ER of C and N was 1.82, which means that the C and N content was 82% higher in the eroded sediment than in the corresponding soil. In PAST, C content in the eroded sediment was only 2% (ER = 1.02) higher than in the soil, while N content was 20% (ER = 1.2) higher. ER values for the remaining treatments were lower than 1. No relationship was found between ER of C and N in sediments and soil loss.

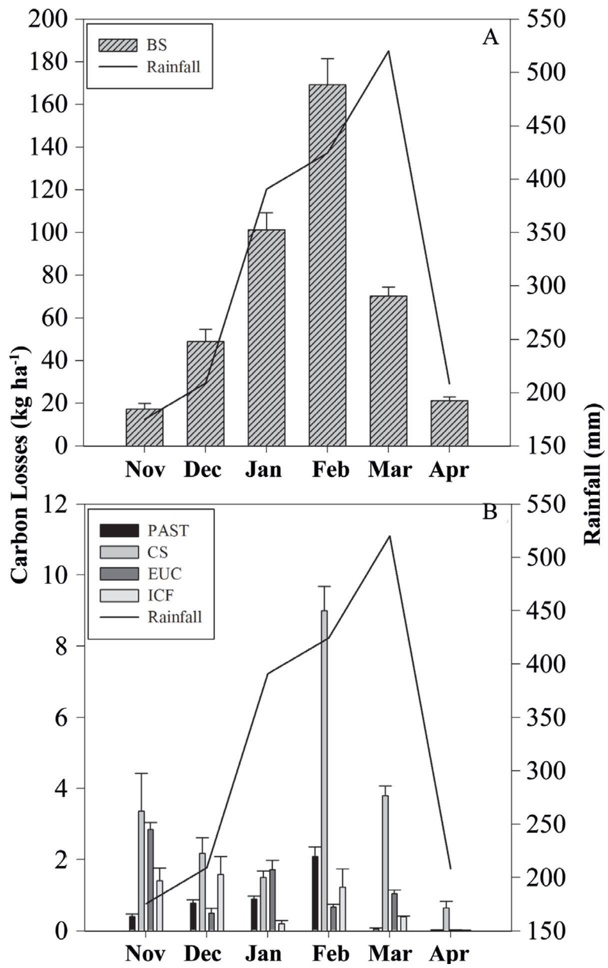

Figure 5. Monthly averages of rainfall and carbon (C) loss in the eroded sediment from experimental plots of different management systems in Sinop, Mato Grosso state, Brazil. A – BS = bare soil; B – PAST = pasture; ICF = integrated crop-forestry system; EUC = eucalyptus plantation; CS = no-tillage system with crop succession. Columns are the mean and bars represent the standard error.

Table 3. C and N content (%) in the eroded sediment (C_{sed} and N_{sed}) and in the soil surface layer ($C_{0.05m}$ and $N_{0.05m}$) used to calculate the Enrichment Ratio for carbon (ER_C) and nitrogen (ER_N) in water-carried sediments from runoff sub-plots installed in experimental plots of different production systems in Sinop (Mato Grosso state, Brazil) from November 2012 to April 2013. PAST – pasture; ICF - integrated crop-forestry system; EUC – eucalyptus plantation; CS – no-tillage with crop succession; and BS - bare soil.

Treatment	$C_{0.05m}$	$N_{0.05m}$	C_{sed}	N_{sed}	ER_C	ER_N
BS	2.78	0.18	2.28	0.16	0.82	0.88
CS	2.80	0.18	2.28	0.16	0.81	0.88
EUC	2.54	0.17	4.00	0.31	1.57	1.81
ICF	2.90	0.18	2.20	0.16	0.76	0.87
PAST	2.76	0.18	2.76	0.21	1.00	1.19

DISCUSSION

Soil and water losses

Our results confirm the findings of other studies in Brazil on the importance of soil cover for soil conservation. A meta-analysis of the Brazilian experience with runoff and soil-erosion plot-scale studies under natural rainfall revealed similar values of soil loss, respectively, 0.1 and 0.3 Mg ha^{-1} year^{-1} in southern and central-western Brazil under pasture and grassland, concluding that conservation practices reduce erosion to ratios of those measured under natural vegetation (Anache *et al.* 2017).

An assessment of soil and nutrient loss and cost of water erosion in southern Brazil using a 22.1 x 3.5-m plot with 10% slope, resulted in soil loss of 85.3 Mg ha^{-1} on bare soil and 9.6 Mg ha^{-1} on conventionally tillaged soil, respectively 25 and 2.8 times higher than soil loss in a no-tillage system (Bertol *et al.* 2017).

In an area of natural savanna in the Brazilian Amazon, a three-month study found that, in addition to the natural vegetation, pasture with *Urochloa brizantha* and corn plantation were more efficient in containing erosion through soil, water, organic carbon and nutrient loss than cowpea-bean plantation and bare soil (Souza *et al.* 2019). In the latter study, average soil and water loss were, respectively, 8.9 and 3.9 times higher in bare soil than in the other treatments, showing that the harmful effects of erosion were attenuated by the soil cover.

However, a medium-term study in the same region of the northern Brazilian Amazon from 1988 to 1992, showed that conversion of primary forest to pasture can increase soil erosion 7.5 fold, which can impact the regional and global social economy (Barbosa and Fearnside 2000). As deforestation increases in the Amazon, unfavorable vegetation and soil conditions can decrease rainwater infiltration and increase surface runoff and sediment yield, which could ultimately cause land degradation (Zhu *et al.* 2018) and affect the hydrological budgets of large watersheds. In this regard, deforested areas converted to pasture lands, are more prone to deliver water with higher solute concentrations generated by erosion (Chaves *et al.* 2008). A recent and extensive literature review showed that soil erosion is the main resilience drain in disturbed tropical forests in the Brazilian Amazon (Flores *et al.* 2019).

Similar results were observed in other tropical regions. The suspended sediment yield from catchments under cropland on the forest frontier in southwestern Ethiopia was found to be four times larger than the yield from similar catchments under forest, with average values of 17 and 4 Mg ha^{-1}, respectively, which was attributed to higher soil erosion rates under cropland (Kassa *et al.* 2019). In Southwest China, the conversion of tropical rainforest to rubber monoculture increased sediment yield from 0.041 to 11.54 Mg ha^{-1}, a

280 fold increase, while the conversion of tropical rainforest to agroforestry systems only increased sediment yield from 0.041 to 2.73 Mg ha^{-1} (Zhu *et al.* 2018).

C and N content in the eroded sediment

Similar values of C and N contents in the soil surface layer were observed in all treatments, which can be explained by the fact that measurements were made during the second year after the experiment was established, and significant management-induced changes in total soil C and N content usually occur in the long term (Silva and Resck 1997).

The higher variability of C and N content observed in PAST and EUC sediments is likely related, on the one hand, to surface residue inputs (mowing of pasture and eucalyptus interrow during the collection period) and, on the other hand, to fertilization inputs in these treatments. In a study on nutrient loss by water erosion in agricultural soils of contrasting organic matter management, the eroded C was mainly derived from fresh organic residue added to the soil, while N loss was primarily associated with soil organic matter loss (Shi and Schulin 2018), corroborating the strong positive correlation between C and N loss observed in our study.

Soil organic C and its related components are preferentially transported by water erosion due to their low density of and that their content is higher in the soil surface layer (Strickland *et al.* 2012; Shi and Schulin 2018). Thus, high contents of C and N in the sediment are not directly related C and N content in the soil surface layer, but to the preferential transport of light organic components, since the content of C and N in the eroded sediment were negatively correlated with soil C and N content in the 0-0.05 m of the original source soils. Similar results were also reported by Owens *et al.* (2002), Girmay *et al.* (2009) and Martinez-Mena *et al.* (2008).

In EUC, the trees were 3.5 to 6 m high during the monitoring period, in a fast-growing stage, when they immobilize a significant amount of resources (water, carbon, and nutrients), and the system is in the open phase, when the biochemical cycling is prevailing (Laclau *et al.* 2010). Thus, it is likely that the C and N content in the EUC sediments were more related to soil management (subsoiling and furrower) and fertilization than to a direct effect of the trees at this stage.

Thus, the adoption of conservation-effective measures is essential to minimize the effects of rainfall erosivity, and to protect the stock of soil organic carbon (Silva *et al.* 2005; Keesstra *et al.* 2016). In Vietnam, total soil C losses of 0.001 and 0.008% were observed in the 0 - 0.10-m layer after a single intense rainfall event, when the lowest C loss was observed for bare soil and the highest for a planted forest (Janeau *et al.* 2014). In a study in the Mediterranean region, agriculture was responsible for 70% of the soil loss by erosion, but for only 45% of the total eroded C, and 55% of the total eroded C was derived from soils under forest (Nadeu *et al.* 2014). Therefore, the management systems that contribute to greater amount of residues on the soil surface are prone to losing some of the organic material by runoff. A proper tillage system can improve soil organic carbon accumulation and benefit land restoration (Wang *et al.* 2018).

In a study comparing the effect of antecedent soil water on sediment-bound carbon and nitrogen loss in the North-American Atlantic coastal plain, higher C and N loss was observed under conventional than under strip tillage (Strickland *et al.* 2012). In a semiarid Mediterranean region with only 386 mm average annual rainfall, Ruiz-Colmenero et al. (2013) reported C losses of 0.02 and 0.06 Mg ha^{-1} yr^{-1} were reported, higher under conventional tillage that under grassland management (Ruiz-Colmenero *et al.* 2013). In southeastern Brazil, where average annual rainfall is 1530 mm, Silva *et al.* (2005) reported C losses from 0.05 to 1.51 Mg ha^{-1} yr^{-1} (average 0.40 Mg ha^{-1} yr^{-1}) in a Rhodic Hapludox soil without vegetation cover.

Monthly and accumulated C and N loss

A decrease in C and N loss in BS was observed during March 2013, despite high rainfall, which was related to soil-surface sealing due to raindrop impact and the lack of organic material on the soil surface (field observation by the authors). The lack of plant residue on the soil surface reduces the selective character of erosion (Silva *et al.* 2005), affecting C loss patterns in our plots, and, consequently, N loss, which was directly related to C loss. The strongly positive relationship between rainfall and C and N loss in BS during the period of intense rainfall (November-February) can be explained by the direct impact of the absence of vegetation cover, combined with soil surface sealing, on the conversion of rainfall into runoff (Zuazo and Pleguezuelo 2008).

The lower monthly soil loss in PAST, ICF and EUC as compared with CS, was also reported by Russelle (1996), indicating the benefits of well-managed pastures for soil conservation. In these treatments, the high correlation observed between rainfall and C loss from November to February may be related to the fact that eroded C was preferentially derived from the fresh organic residue present in the soil surface, as pointed out by Shi and Schulin (2018).

In general, soil and nutrient losses are higher during the early stages of crop establishment because of the bare soil, resulting in higher impact of highly erosive rains (Silva *et al.* 2005, Leite *et al.* 2009, Rieger *et al.* 2016), which is corroborated by our observation of highest values of C and N loss in February for CS. Moreover, our results indicate that even after a short-term period, the ICF system can have a positive synergetic effect on soil, water, and nutrient loss when compared to CS, as after two years, we observed a reduced water loss in ICF relative to PAST and EUC.

The cumulative losses and average contents of C and N in eroded sediments in our treatments indicated that the highest total losses did not necessarily correspond with the highest contents of C and N in the eroded sediment. This trend was especially evident in EUC, which had the highest content of C and N in the eroded sediment, but a total loss similar to ICF and PAST. Total C and N loss is related to the magnitude of the soil eroded (Schick *et al*. 2000; Santos *et al*. 2007), which is relevant to the total losses recorded in our study. In this regard, Suescún *et al*. (2017) also observed higher soil and nutrient losses under crop systems when compared to pastureland and oak forest.

Enrichment ratio

The ER of C and N for eroded sediment in EUC was probably related to the surface residue inputs (weed control by mechanical mowing in March 2013), which contributed to increasing SOC in the surface layer (easily transported by the water runoff) and the fertilization inputs, as previously mentioned. The ER of N for eroded sediment in PAST may be attributed to the transport of organic material as a consequence of mowing of pasture during the collection period (February 2013), contributing to a greater amount of residues on the soil surface, which was also observed by Shi and Schulin (2018).

Results similar to those observed for EUC and PAST were reported by Dedecek *et al*. (1986) and Schick *et al*. (2000). However, no ER was observed for BS, NT and ICF, as also reported by Eltz *et al*. (1984).

The ER for nutrients and organic C is partly attributed to selective erosion, as sediments of small diameter or low density (i.e., clay and organic matter) are most likely transported by the runoff, when compared to sediments that remain in the soil (i.e., silt and sand) (Langdale *et al*. 1985). This size-selective process may result in higher nutrient contents in sediments than in the source soil (Shi *et al*. 2018). Also, antecedent soil moisture may play an important role in this process, increasing runoff and sediment erosion in tilled soils through slaking of newly-formed, nonwater stable aggregates, which increases the proportion of high carbon silt + clay particles eroded during runoff (Strickland *et al*. 2012).

CONCLUSIONS

In this study we provided relevant insights on the short-term effect of a crop-livestock-forestry system on soil, water and nutrient losses in one of the most important and vulnerable agricultural frontiers in Brazil. We observed that both C and N loss was lower for production systems with tree components compared with a no-tillage crop succession system, indicating their higher capacity to reduce soil loss throughout the rainy season. Our results support the notion that ICLF systems can provide benefits for the Cerrado-Amazon ecotone sustainable agriculture management, with reduced soil, water, and nutrient loss. Moreover, we showed that, even under a short-term period of establishment, a positive synergetic effect for soil, water, and nutrient conservation is obtained through ICLF. Our results should encourage further studies to increase scientifically sound information on soil, water and nutrient loss under different production systems, to support policymakers to seek more sustainable approaches for this crucial agricultural and environmentally sensitive region of Brazil.

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