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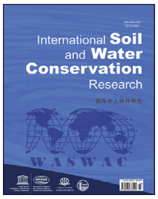

Original Research Article

Ecological intensification of cropping systems enhances soil functions, mitigates soil erosion, and promotes crop resilience to dry spells in the Brazilian Cerrado

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ABSTRACT

Water scarcity threatens global food security and agricultural systems are challenged to achieve high yields while optimizing water usage. Water deficit can be accentuated by soil physical degradation, which also triggers water losses through runoff and consequently soil erosion. Although soil health in cropping systems within the Brazilian Cerrado biome have been surveyed throughout the years, information about soil erosion impacts and its mitigation are still not well understood; especially concerning the role of cropping system diversification and its effects on crop yield. Thus, the aim of this study was to assess whether ecological intensification of cropping systems −inclusion of a consorted perennial grass and crop rotation− could promote soil coverage and consequently decrease water erosion and soil, water, and nutrient losses. This work studied the effects of crop rotation and consorted *Brachiaria*, along with different levels of investment in fertilization on soil physical quality and on soil, water, and nutrient losses, and crop yields. Results proved that soybean monoculture (SS) is a system of low sustainability even under no-till in the Brazilian Cerrado conditions. It exhibited high susceptibility to soil, water, and nutrient losses, causing low crop yields. Our results showed that water losses in SS cropping system were approximately 10% of the total annual rainfall, and total K losses would require an additional 35% of K application. Conversely, ecological intensification of cropping systems resulted in enhanced soil environmental and agronomic functions, increased grain yield, and promoted soil and water conservation: high soil cover rate, and low soil, water and nutrient losses. Ecological intensification proved to be an adequate practice to boost crop resilience to water deficit in the Brazilian Cerrado.

1. Introduction

Regions with characteristic dry periods require strict soil management practices to maintain crop production as climate changes are expected to aggravate water scarcity and soil degradation, two critical factors for crop production (IPCC, 2013). Future production systems must impact positively the capacity of soils to sustain biological productivity −within their microbiome and land use scales−, to maintain environmental quality, and to promote plant and animal health while achieving high crop yields (NASEM, 2019).

Abbreviations: AC, air capacity; Bd, bulk density; CR, cover rate; GMD, geometric mean diameter; Ma, macroporosity; Mi, microporosity; MWD, mean weight diameter; MY, maize yield; NT, no-till; OC, organic carbon; PAWC, plant available water capacity; RFC, relative field capacity; SL, soil losses; SY, soybean yield; Tp, total porosity; WL, water losses; WSA, water stable aggregates.

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No-Till systems (NT) have progressively been adopted by farmers over conventional soil tillage. NT promotes soil and water conservation as minimum soil disturbance occurs (Blevins et al., 1971; Derpsch et al., 2010; Lal et al., 2007). It is estimated that 180 million hectares are under NT throughout the world (Kassam et al., 2018) and 32 million hectares in Brazil (Peixoto et al., 2019). NT is based on three defining conservation practices: a) absence of —or minimum— soil turnover; b) constant maintenance of plant cover on the soil surface, and c) diversification of plant species (Kassam et al., 2018). These practices play important roles for increasing crop productivity, especially at rain-fed agriculture sites (Asmamaw, 2017). Nevertheless, regional limitations may threaten the success of NT systems. In Brazil, soil compaction (Peixoto et al., 2019, 2020) and the lack of soil cover (Didoné et al., 2017; Merten et al., 2015) have been reported as the main limitations for the sustainability of NT production systems, and there is still a quest for alternatives to overcome those issues, especially in the Cerrado (neotropical savanna) biome.

Oxisols (Latosols) constitute the main soil class in Brazil —a country of continental proportions— corresponding to more than 60% of the country's surface (Schaefer et al., 2008), and approximately half of the Brazilian Cerrado biome (Eberhardt et al., 2008). Oxisols present high degrees of leaching and weathering, resulting in substantial contents of gibbsite in the clay fraction (Ferreira et al., 1999; Ker, 1997). Moreover, Oxisols exhibit severe chemical restriction to plant development as these soils have low cation exchange capacity (CEC), high aluminum saturation, and low nutrient availability (Goedert, 1983; Lopes, 1984; Lopes & Cox, 1977). However, when these soil fertility limitations are resolved by the application of soil amendments and fertilizers, these soils present high yield potential (Castro & Crusciol, 2013; Goedert, 1983); *e.g.*, physical soil properties are optimal for plant growth.

Additionally, Oxisols exhibit granular structure, low bulk density, high macro- and microporosity, high aggregate stability, high infiltration rate, low mechanical resistance to root penetration, and they are mostly found on relatively smooth topography, which makes them suitable for large scale mechanized agriculture (Ferreira et al., 1999; Goedert, 1983; Ker, 1997; Severiano et al., 2011; Silva et al., 2015). Although these soils have high water retention, they have low plant available water capacity (PAWC), due to almost null presence of mesopores (Carducci et al., 2013; Silva et al., 2014, 2015); *i.e.*, abrupt transition in their pore size distribution, from very large pores to very small pores.

In regions like central Minas Gerais, Brazil —a region within the Cerrado biome with a prolonged dry season in winter and frequent occurrence of dry spells (*veranicos*) in the warm rainy season— the soil PAWC becomes a physical restriction that challenges crop production; *e.g.*, crop yield is compromised due to water deficit at critical phases of crop development. Not limited to Brazil, recent projections indicate that water scarcity is a major issue in the upcoming decades (IPCC, 2013; Mancosu et al., 2015). Furthermore, as water stress is the main limiting factor for agricultural crops (Silva et al., 2019; Srayeddin & Doussan, 2009), global food security is at risk.

Among conservation practices, soil cover is crucial to avoid water losses through runoff and evaporation (Zuazo & Pleguezuelo, 2008; Cardoso et al., 2012; Sharma et al., 2018; Peixoto et al., 2020; Santos et al., 2021). It has been reported that soil cover is a key factor for increasing crop yields in locations with rainfed agriculture (Asmamaw, 2017; Borghi & Crusciol, 2007; Calonego et al., 2011; Chioderoli et al., 2012; Crusciol et al., 2012, 2014; Moura et al., 2021). Crop rotation combined with cover crops can provide beneficial ecosystem services (TerAvest et al., 2019), increase soil organic carbon content and reduce soil compaction (Cherubin et al., 2016; Dexter, 2004). Regarding locales susceptible to water deficit, diversification of NT cropping systems provides water stress resistance improvements (Degani et al., 2019) resulting in more stable and resilient cropping system productivity (Madembo et al., 2020), as well as improved soil health and high yields (Huynh et al., 2019; Nunes et al., 2018). For instance, in Mediterranean ecosystems the use of cover crops proved to increase infiltration rates (Cerdà & Rodrigo-Comino, 2021), and reduce runoff and sediment yield (Rodrigo-Comino et al., 2020). Furthermore, consorted and off-season cover crops improve soil-water dynamics and promote deep root systems growth (Novara et al., 2021). This allows plants access deeper available water and meet crop water requirements to achieve full production potential (Carducci et al., 2013; Silva et al., 2015, 2019). Nonetheless, large agricultural areas in Brazil exhibit low productivity and environmental degradation, which made the sustainable intensification of cropping systems an ongoing challenge to be addressed (Reis et al., 2021). Thus, environmental and agricultural soil functions, as well as their effects on crop production of intensified cropping systems are key factors yet to be investigated in the Brazilian Cerrado, a region of agricultural expansion (Soterroni et al., 2019).

Concerning soil functions regulated by soil physical quality, water infiltration rate and water percolation influence directly on the soil erosion processes. Soil and water losses caused by surface runoff remove agricultural inputs —fertilizers, herbicides, and other agricultural chemicals— along with detached soil particles (Norton et al., 1999). The effects of erosion lead to direct losses for farmers, *e.g.,* soil degradation, nutrient losses, and compromised crop yield (Panagos et al., 2018; Pimentel et al., 1995). In addition to direct damage, there is indirect damage, such as silting and eutrophication of water bodies due to sediment and agricultural inputs transportation (Blanco-Canqui & Lal, 2008). Such losses are ultimately paid by society in general (Panagos et al., 2018). Therefore soil erosion not only poses a threat to agriculture sustainability and to environmental conservation, but also has socioeconomic implications (Borrelli et al., 2017).

Although soil health in cropping systems within the Brazilian Cerrado biome have been surveyed throughout the years, information about soil erosion impacts and its mitigation are still not well understood (Falcão et al., 2020); especially concerning the role of cropping system diversification and its effects on crop yield. Thus, the aim of this study was to assess whether ecological intensification of cropping systems —inclusion of a consorted perennial grass (*Brachiaria*), and crop rotation— could promote greater soil coverage and consequently decrease water erosion and soil, water and nutrient losses. This work studied the effects of crop rotation including off-season consorted *Brachiaria*, along with different levels of investment in fertilization on soil physical quality, on soil, water, and nutrient losses, and crop yields. Our hypothesis was that ecological intensification of cropping systems would promote physical benefits such as improved soil structure by substantial production of grass biomass and vigorous root systems, resulting in positive impacts on grain yield, and decreasing soil, water and nutrient losses. Our hypothesis was based on previous studies that have proved suitability and benefits of including *Brachiaria* in crop rotation systems (Borghi & Crusciol, 2007; Calonego et al., 2011; Chioderoli et al., 2012; Crusciol et al, 2012, 2014; Moura et al., 2021).

2. Materials and methods

2.1. Study area

The study was conducted on the experimental farm of the Brazilian Agricultural Research Corporation (Embrapa Maize and Sorghum) in the municipality of Sete Lagoas, Minas Gerais, Brazil, at

19°28′30″ S, 44°15′08″ W (Fig. 1). Predominant climate in the region according to the Köppen climate classification is humid subtropical (Cwa), with mean annual temperature of 22.1 °C, and mean annual rainfall of 1382.7 mm (Alvares et al., 2013; Borges Junior et al., 2017), mainly concentrated from October to April (Fig. 2). This region has a characteristic dry season with frequent occurrence of dry spells during the rainy season. The soil was classified as Typic Haplustox (Soil Survey Staff, 2014), which corresponds to a *Latossolo Vermelho distrófico típico* (Santos et al., 2013) with gibbsitic mineralogy (Galvão and Schulze, 1996). Regarding particle size distribution the soil has 690 g kg^{-1} of clay ($\varnothing$<0.002 mm), 120 g kg^{-1} of silt (0.002–0.05 mm), and 190 g kg^{-1} of sand (0.05–2 mm), corresponding to a soil with very clayey texture.

The experiment was set up in July 2014 under rainfed conditions. The experimental site has a total area of 4.4 ha and prior to experimental set-up, the area had been used for maize and soybean production under conventional soil tillage for more than two decades. Experimental set-up began by chisel plowing the soil to a depth of 25 cm to break compacted layers. Dolomitic limestone was applied at a rate of 4 t ha^{-1}, apportioned in two operations: the first incorporated with a moldboard plow, and the second using a disk plow. Agricultural gypsum was also applied at a rate of 3 t ha^{-1}. The experimental area was divided in stripes with terraces between each other. A large experimental block was implemented using each stripe for a different treatment as explained in section 2.2.

Fig. 3 shows ground-level photography (Fig. 3a and b) of the experimental site (Fig. 1c), and provides graphic information portraying *in-situ* sampling (Fig. 3c, d, e, j) and laboratorial analyses (Fig. 3f, g, h, i) throughout the experiment.

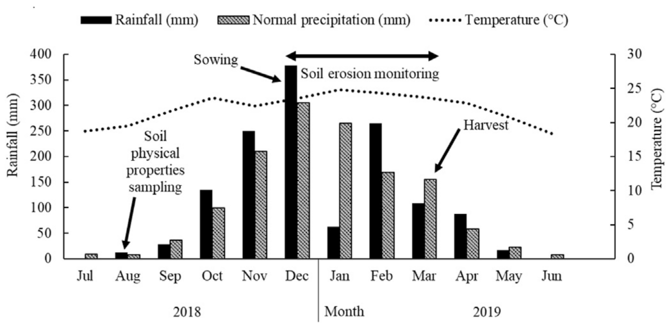

Fig. 2. Temperature and monthly precipitation data during the monitoring period (August 2018 to July 2019). The normal precipitation corresponds to the period from 1927 to 2013 (Borges Junior et al., 2017).

2.2. Treatments

Six NT treatments were evaluated (Fig. 1c). They differed from each other by utilized management practices: a) different crop rotation systems, b) intercropped *Brachiaria*, and b) level of investments of fertilizer application (Table 1). Continuous soybean (SS) and maize (MM) monocultures were compared to cropping systems including crop rotation: maize-soybean succession (MS),

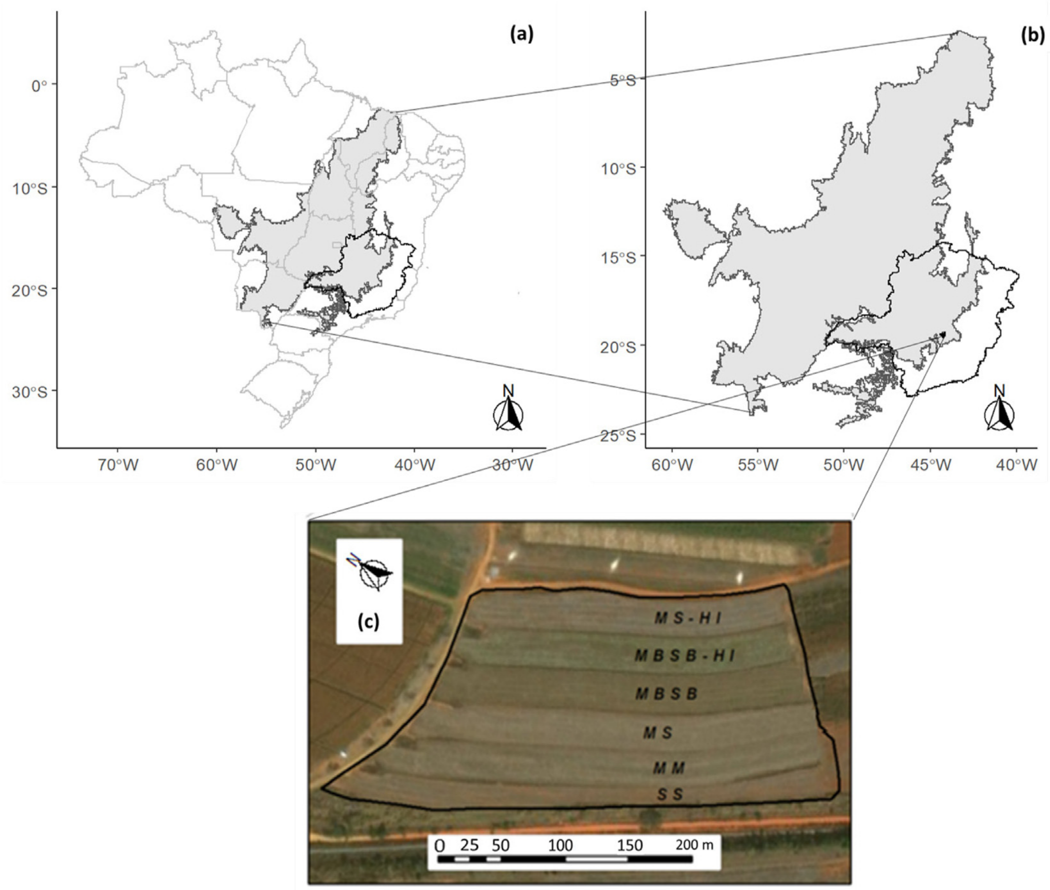

Fig. 1. Cerrado biome and the state of Minas Gerais in Brazil (a), municipality of Sete Lagoas in the central region of Minas Gerais (b), and aerial photography of the experimental site (c). SS = soybean monoculture, MM = maize monoculture, MS = maize/soybean rotation, MBSB = maize/brachiaria/soybean/brachiaria rotation, BS = bare soil, and HI = high input of fertilizers.

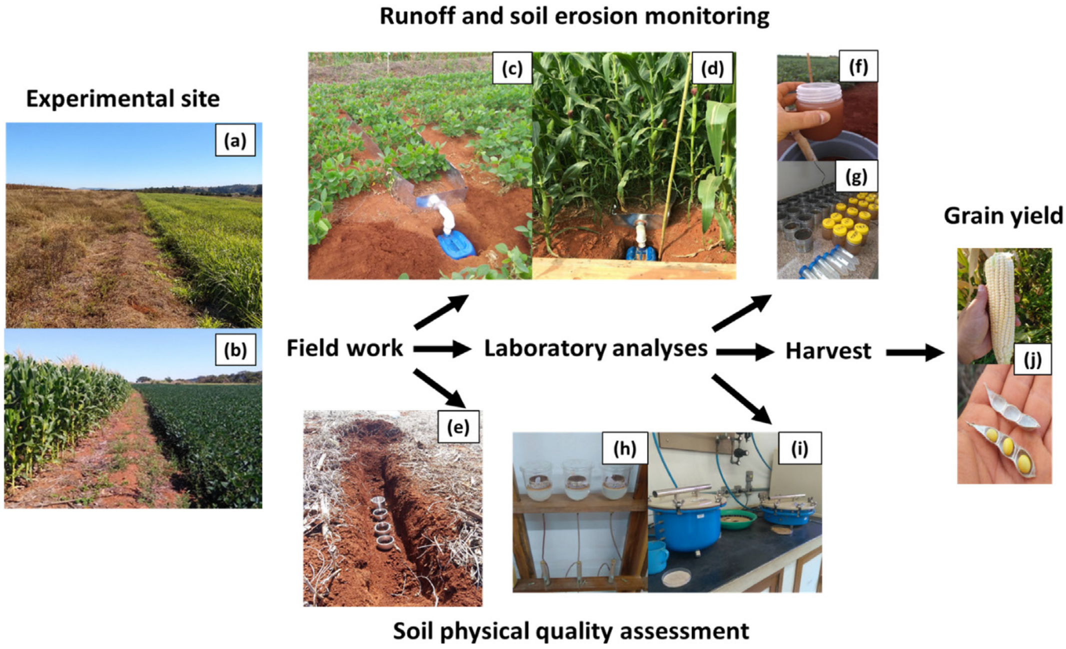

Fig. 3. Ground-level photography of maize/soybean succession (left – in fallow) and maize/brachiaria/soybean/brachiaria rotation (right – brachiaria) in the winter (a); Ground-level photography of maize monoculture (left) and soybean monoculture (right) in the summer (b); Runoff plots in soybean monoculture (c) and in maize/brachiaria/soybean/brachiaria rotation (d); Undisturbed soil sampling (e); Runoff water and sediments sampling (f); Laboratory procedures for soil and nutrients losses quantification (g); Laboratory procedures for soil physical properties assessment (h and i); Maize and soybean yield evaluation (j).

Table 1
Crop systems in each crop year in a Typic Haplustox in the central region of the State of Minas Gerais, Brazil.

Soil management system	Level of investment in fertilization	Year 2014/2015 Summer	Year 2015/2016 Summer	… [a]	Year 2018/2019 Summer	Pre-harvest season Autumn-Spring
SS	Medium	Soybean	Soybean		Soybean	Fallow
MM	Medium	Maize	Maize		Maize	Fallow
MS	Medium	Maize	Soybean		Maize	Fallow
MBSB	Medium	Maize + brachiaria	Soybean + brachiara		Maize + brachiaria	Brachiaria
MBSB-HI	High	Soybean + brachiaria	Maize + brachiaria		Soybean + brachiaria	Brachiaria
MS-HI	High	Soybean	Maize		Soybean	Fallow

SS = soybean monoculture, MM = maize monoculture, MS = maize-soybean rotation, MBSB = maize-brachiaria-soybean-brachiaria rotation, HI = high input of fertilizers.
[a] 2016/2017 repeats 2014/2015, and 2017/2018 repeats 2015/2016.

and maize-*Brachiaria*-soybean-*Brachiaria* rotation (MBSB). In addition, two different levels of investment of fertilizer application were evaluated. The medium level of investment was adopted as our baseline, as it contemplates a tipical maintenance fertilization used by producers in the region, while the high level of investment (HI) considers an extra input of fertilizers aiming at higher yields.

For the 2018/2019 crop season, soybean (cultivar RK 5813 RR) and maize (cultivar AG 8088 Pro2) were sown at the density of 320,000 and 61,000 seeds per hectare, respectively. Maize was sown at a spacing of 70 cm between crop rows and soybean at a spacing of 50 cm between rows. For the Brazilian Cerrado, these different spacing between rows provide adequate plant conditions for crop development. Fertilization consisted of totally supplying (high level of investment), or partially supplying (medium level of investment) the nutrient demands for high potential yield of the crops.

The levels of investment in fertilizers were adapted from the recommendations of Sousa and Lobato (2004, p. 416) for maize and soybean in the Brazilian Cerrado region and have been applied since the experimental set-up in 2014/2015. In the 2018/2019 crop season, 134, 250, 250, 250, 390, and 390 kg ha^{-1} of the NPK formulation 08-28-16 + 0.3% boron, and 2.1% sulfur were supplied for the SS, MM, MS, MBSB, MBSB-HI, and MS-HI treatments, respectively. The results of soil chemical analysis before sowing in 2018/2019 are described in Table 2.

For treatments MBSB and MBSB-HI, the seeds of *Brachiaria* species *Urochloa ruziziensis* were sown at a rate of 4 kg ha^{-1}, varying the time of planting according to the consorted crop. *Brachiaria* seeds were mixed with fertilizers and sown into the soil using a precision seeder/fertilizer spreader at the maize line. Meanwhile a mechanical broadcast seeder was used for *Brachiaria* seeds when soybean plants reached the R5 growth stage as described by Andrade et al. (2017).

2.3. Soil physical properties: sampling and processing

Undisturbed soil samples were collected in three georeferenced points, being three replicates for each treatment, in August 2018, with metallic cylinders at two soil depths (0–0.05 and 0.15–0.20 m). We used an Uhland type sampler for evaluation of soil bulk density (Bd), total porosity (Tp), macroporosity (Ma), microporosity (Mi), plant available water capacity (PAWC), aeration

Table 2
Chemical characterization for each treatment in each depth before sowing.

Depth (m) 0–0.10	Soil management system					
	SS	MM	MS	MBSB	MBSB-HI	MS-HI
pH (H_2O)	5.94	5.61	5.72	5.62	6.02	6.39
pH ($CaCl_2$)	5.39	4.96	5.06	5.02	5.42	5.86
P (mg dm^{-3})	19.43	33.43	21.10	23.74	14.93	26.85
K (mg dm^{-3})	180.02	183.05	190.35	192.12	206.56	212.24
S (mg dm^{-3})	3.61	3.15	3.76	4.06	4.55	3.61
Ca (cmolc dm^{-3})	4.26	3.22	3.97	3.61	3.74	4.26
Mg (cmolc dm^{-3})	1.31	0.92	0.96	1.10	1.05	1.09
B (mg dm^{-3})	0.43	0.40	0.62	0.49	0.59	0.61
Cu (mg dm^{-3})	0.75	0.77	1.01	0.93	0.72	0.86
Fe (mg dm^{-3})	25.01	28.25	29.16	28.80	24.15	23.02
Mn (mg dm^{-3})	46.04	44.58	52.61	57.35	59.99	67.87
Zn (mg dm^{-3})	22.72	34.63	27.96	26.21	15.76	24.80
Al (cmolc dm^{-3})	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
H + Al (cmolc dm^{-3})	3.69	5.20	4.84	5.28	4.57	3.45
CEC (cmolc dm^{-3})	9.73	9.82	10.28	10.48	9.91	9.35
V (%)	61.60	51.57	52.80	49.60	53.67	61.64
m (%)	0.00	0.00	0.00	0.00	0.00	0.00
Depth (m) 0.10–0.20						
pH (H_2O)	5.68	5.57	5.47	5.44	5.57	5.89
pH ($CaCl_2$)	5.11	4.98	4.83	4.82	4.95	5.33
P (mg dm^{-3})	11.32	12.45	13.09	12.59	8.70	10.79
K (mg dm^{-3})	120.10	106.78	155.69	170.10	138.30	153.52
S (mg dm^{-3})	5.68	6.05	6.41	6.21	6.59	5.75
Ca (cmolc dm^{-3})	3.97	4.06	4.32	3.99	3.74	5.08
Mg (cmolc dm^{-3})	1.08	0.95	0.93	0.87	0.86	1.26
B (mg dm^{-3})	0.38	0.44	0.50	0.69	0.71	0.64
Cu (mg dm^{-3})	0.77	0.80	0.90	0.83	0.68	0.69
Fe (mg dm^{-3})	30.01	33.01	37.09	30.81	25.39	21.92
Mn (mg dm^{-3})	37.59	44.11	53.00	59.74	52.46	62.60
Zn (mg dm^{-3})	8.81	18.98	10.18	11.78	8.14	11.62
Al (cmolc dm^{-3})	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
H + Al (cmolc dm^{-3})	4.89	5.12	5.40	5.50	4.84	4.23
CEC (cmolc dm^{-3})	10.25	10.39	11.04	10.82	9.79	10.97
V (%)	51.60	51.00	51.20	49.22	50.60	61.45
m (%)	0.00	0.00	0.00	0.00	0.00	0.00

SS = soybean monoculture, MM = maize monoculture, MS = maize/soybean rotation, MBSB = maize/brachiaria/soybean/brachiaria rotation, HI = high input of fertilizers.

capacity (AC), and relative field capacity (RFC). Soil clod samples also were collected with the aid of a mattock for water stable aggregates (WSA), and deformed soil samples were collected with an auger for organic carbon (OC) for both cases samples were collected from the top 20 cm soil layer. Soil samples were collected outside the erosion plots to avoid any possible disturbance which could impact the erosion processes.

The saturated undisturbed samples were placed under the matric potential of −6 kPa in Büchner funnels (Fig. 3h) (Grohmann, 1960; Oliveira, 1968), as well as −10 and −1500 kPa in a Richards Chamber (Fig. 3i) (Klute, 1986, pp. 635–662). Total, macro-, and microporosity, together with Bd and PAWC were determined and calculated according to Teixeira et al. (2017). Aeration capacity (AC) and relative field capacity (RFC) were used as indicators of soil aeration and soil water storage and were calculated according to Reynolds et al. (2008). Organic carbon (OC) was calculated by conversion of the organic matter content determined in routine chemical analysis (dry combustion) by the van Bemmelen factor.

For water-stable aggregate size distribution, soil aggregates passed through an 8.0-mm sieve and retained at a 4.75-mm sieve were used. For each replicate, aggregates corresponding to 25 g of dry soil were utilized. The samples were pre-wetted by capillary motion and then placed under vertical shaking in water in a sieve set with meshes of 2.0, 1.0, 0.5, 0.25, and 0.105 mm, according to the apparatus proposed by Yoder (1936), for 15 min. Geometric Mean Diameter (GMD), Mean Weight Diameter (MWD), and percentage of Water Stable Aggregates (WSA) were calculated according to Teixeira et al. (2017).

2.4. *Soil erosion: sampling and processing*

During this work (2018/2019), we installed erosion plots —after sowing— within each treatment to measure soil, water, and nutrient losses. This corresponded to the assessment of treatment effects during the fifth year (2018/2019) of experimental set-up. Field campaigns for this work took place between August 2018 (winter) and March 2019 (summer). Before field campaigns we georeferenced ten random points for data collection. Monitoring of erosion plots occurred from December 2018 to March 2019; *i.e.* the crops cycle.

The experimental unit for evaluation of soil and water losses was composed of erosion plots, as suggested for the standard unit plot or erosion plot by Wischmeier & Smith (1978). Set-up consisted of three replicates within each treatment, as well as an additional treatment of bare soil (BS), which was kept devoid of crops and weeds. Weeds were controlled manually at BS plots. As mentioned, terraces were built between treatments (Fig. 1c). This practice restricted any possible runoff flowing from upside plots to lower-level ones.

Erosion experiments focusing on the parameterization of a given model, such as USLE/RUSLE, must have slope lengths greater than one or 2 m (Kinnell, 2016). However, as this study did not intend to model water erosion, the plots were 2-m long. The 1.0-m^2 (0.5 × 2.0 m) erosion plots were delimited by galvanized steel plates of 0.3-m width, which were inserted into the soil to a depth of 0.10 m. The 2-m length was aligned with the land slope direction. In the lower part of the plots, a PVC tube was adapted, directing the water and sediments towards a 25-dm^3 collection containers (Fig. 3c), which were set up in open pits below the plots (Fig. 3d).

After rainfall events –individual or combined– runoff material was sampled from the collection containers. Soil loss for each treatment was obtained by quantification of the eroded sediments in the experimental plot, which was expressed in total soil loss (Mg ha^{-1}), and surface runoff was expressed in total water loss (mm). These results corresponded to the losses measured for the fifth year of treatments, crop cycle 2018–2019. The slope of each plot was measured separately ranging from 7 to 10%, and the soil erosion results were adjusted for a standard 9% slope according to Eq. (1) (Wischmeier & Smith, 1978):

$$S = 4.56 \sin\theta + 65.41\,(\sin\theta)^2 + 0.065 \tag{1}$$

where S is the slope factor and θ is the slope angle (degrees).

The volume of water lost by surface runoff was determined by subtracting the weight of sediments. Sediments were quantified using 250-mL samples of the homogenized collected volume. Each 250-mL sample received 3 drops of 50% concentration HCl to allow flocculation of suspended particles, the excess of water was then decanted. Sediment weight was measured after 48 h in a laboratory oven at 105 °C, and nutrients in sediments were determined based on Teixeira et al. (2017). For dissolved nutrient losses in runoff water, a filtered 20-mL aliquot was sampled for the determination of P, K, Ca, Mg, Fe, Zn, Cu, and Mn contents via the optical emission spectrometry in inductively coupled plasma (ICP) technique (Teixeira et al., 2017).

2.5. *Crop yield and soil cover sampling*

The soil cover rate (CR) was determined through manual and complete collection of plant residue within erosion plots before crop harvesting. Crop yield (Mg ha^{-1}) was quantified via the sampling of 5 georeferenced points (replicates) within each treatment. We manually collected three 3-m-length rows to compose a replicate at each georeferenced point (Fig. 3j).

2.6. Statistical analysis

A completely randomized design was adopted considering georeferenced locations —chosen at random— as replicates within each treatment. This statistical methodology for field experiments with one experimental block and long-term experimental set-ups (Ferreira et al., 2012) has been successfully used in prior studies (Cecagno et al., 2016; Moura et al., 2021; Peixoto et al., 2019).

Soil physical properties were analyzed by analysis of variance (ANOVA) using linear mixed-effects model ("lmer" function) in the R environment (R Core Team, 2018) to consider the effect of 2-depth sampling at a single point. Thus, sampling point effect was included in the model as a random effect for soil properties measured at two different depths. Soil physical properties were statistically compared for the crop season 2018/2019 while 2015 data were only provided as a reference of initial conditions. ANOVA was carried out for soil physical properties, soil cover rate, soil losses, water losses, nutrient losses, and crop yield. The means were compared using the Tukey's test at a 5% significance level.

After checking heteroscedasticity in distribution of water losses (WL) through surface runoff, soil losses (SL), and nutrient losses (see supplementary data), data were analyzed using generalized least squares (GLS) to allow estimation of variance for each treatment separately (Cleasby & Nakagawa, 2011; Silva Junior et al., 2017). This approach was based on the suggestion that heterogeneity of variance represents important additional information about data pattern (Cleasby & Nakagawa, 2011), and other studies evaluating soil erosion have also reported heteroscedasticity (Dunaway et al., 1994; Polyakov et al., 2020). In addition, principal component analysis (PCA) was carried out along with clustering of individuals based on the observed variables. For correlation matrix, the Spearman rank correlation method was used. This methodology allows linear relation analysis of data that lacks homogeneity.

3. Results

3.1. Soil physical quality

The results of soil physical properties are presented in Fig. 4 and Table 3. Data from 2015 corresponds to initial conditions of the experiment while statistical comparisons were only performed for 2018 data. Overall, management systems exhibited significant differences in physical properties at the upper surface layer (0–0.05 m). The MBSB treatment had greater macroporosity than MS-HI (Fig. 4). Considering NT effects on macroporosity (Ma), all treatments showed Ma values within the optimal limit defined by Reynolds et al. (2008) at both depths, except for MS-HI, which had a value below the lower limit, but differed only from MBSB.

Bd and PAWC values did not exhibit significant differences among treatments at any depth (Table 3). In contrast, air capacity (AC) and relative field capacity (RFC) showed statistical differences among cropping systems at the top layer (0–0.05 m) (Table 3). The MBSB treatment presented significant statistical differences in AC (greater) and RFC (lower) when compared with the MS-HI treatment. Thus, comparing MBSB and MS-HI, intercropped *Brachiaria* seems to have promoted an increase of larger pores and consequently increased soil aeration —yet without any negative impact on water retention. Nevertheless, MBSB (and MBSB-HI) did not differ from other treatments, including those of continuous monoculture, thus not providing enough statistical evidence regarding the *Brachiaria* effects on soil aeration under the assessed conditions of this study.

The indices used to assess soil aggregate stability (*i.e.*, GMD, MWD, and WSA) did not present significant differences among treatments. No significant differences among cropping systems were computed for organic carbon contents (Table 3). Therefore, after 4 years of NT-based cropping systems, there were no observed statistical differences among treatments regarding aggregate stability parameters.

3.2. Soil cover and soil, water, and nutrient losses

The quantity of plant residues that remained on the soil before crop harvesting was expressed by cover rate (CR), and graphically depicted in Fig. 5. The SS and MS treatments resulted in the lowest CR values among treatments. As expected, treatments with intercropped *Brachiaria* presented high CR values, being CR value of MBSB-HI the greatest numerically, nevertheless, no significant difference ($p < 0.05$) was computed for MBSB-HI and MBSB treatments.

Results for soil, water, and nutrient losses are shown in Fig. 6 and Table 4. Erosion plots at soybean monoculture (SS) and bare soil (BS) presented the greatest soil, water, and nutrient losses; *i.e.*, SS and BS plots were more vulnerable to soil erosion processes. Cropping systems with consorted *Brachiaria* were consistently in the same statistical class, grouping those treatments, in general, with low values of soil, water, and nutrient losses. Considering soil cover rate (CR), high values were promoted by intercropped *Brachiaria* (MBSB and MBSB-HI), resulting in reduction of soil and water losses. Thus, our results provide initial insights for future research addressing these interactions.

Nutrient losses (Table 4) were the lowest in cropping systems involving consorted *Brachiaria* (MBSB and MBSB-HI), followed by maize/soybean rotation treatments (MS and MS-HI), and maize monoculture (MM). Conversely, the greatest nutrient losses by erosion, —considering nutrients in water and sediments— expressed in kg ha^{-1}, were observed at treatments SS and BS. Total losses of nutrients (elements) were in the following decreasing order: Ca, Fe, K, Mg, and P, these results are in accordance with those reported by Silva et al. (2005) for an Oxisol using a standard unit plot.

Summarizing, these results highlight the low sustainability of soybean monoculture in our study region where concentrated rainfall distribution, and occurrence of dry spells are inherent to the area of study. Nevertheless, different rainfall patterns can be found across the Brazilian Cerrado biome. Finally, the results are supportive to the usage of intercropped *Brachiaria* in high yield cropping systems, to contribute to high soil cover rate, and consequently reduce surface runoff and increase water infiltration.

3.3. Crop yield

Maize (MY) and soybean (SY) grain yields for the 2018/2019 crop season are shown in Fig. 7. For the maize yields, the MBSB cropping system resulted in greater yield than maize monoculture (MM), although it did not differed from MS. Treatments in which soybean was sown did not show significant differences. Error bars in Fig. 7 represent standard deviation; thus, high sampling variability was observed at treatments with soybean cultivation.

Principal component analysis (PCA) and clustering for variables evaluated in the soil surface layer are shown in Fig. 8a, and the matrix of Spearman correlation for the same variables is depicted in Fig. 8b. These analyses were conducted for the top soil surface layer. The PCA results identified a specific cluster for soybean monoculture, highlighting this treatment as specifically influent and

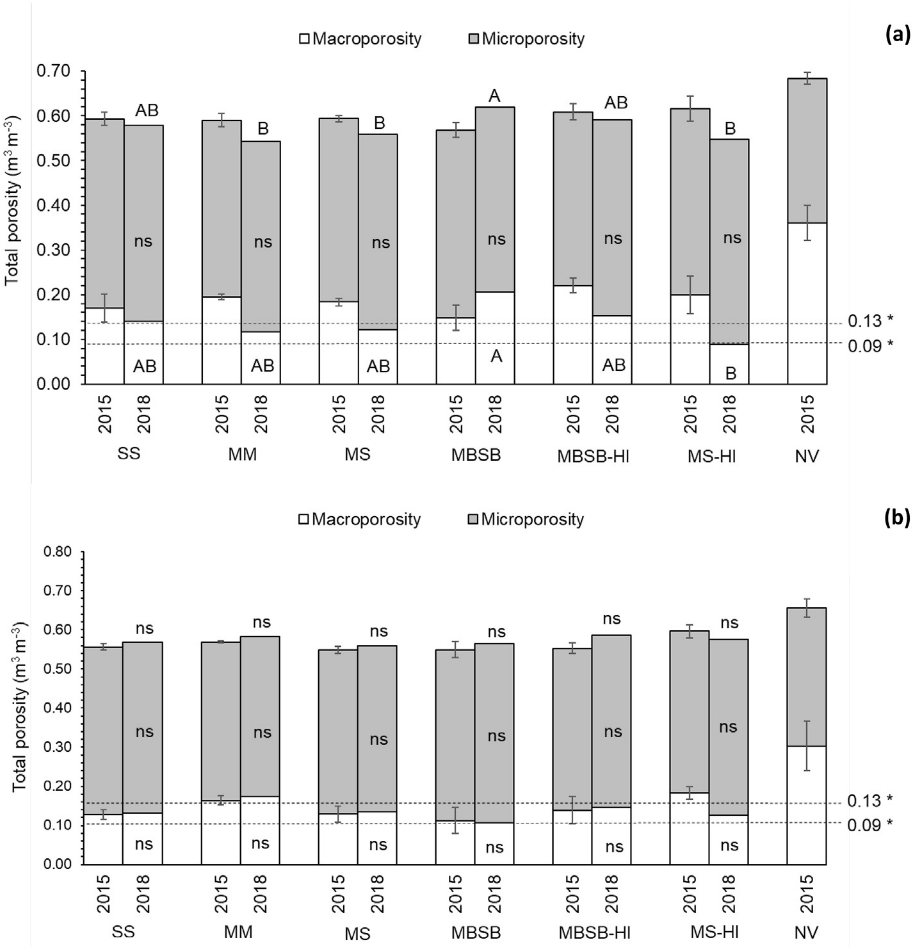

Fig. 4. Total porosity, microporosity, and macroporosity of soil at the 0–0.05 m (a) and 0.15–0.20 m (b) depth for each treatment in the first year of no-till (2015) and in 2018. Data from 2015 represents the initial condition of the experiment and the error bar represents standard error. Means in 2018 followed by different letters differ by Tukey's test ($p < 0.05$), ns = not significant. SS = soybean monoculture, MM = maize monoculture, MS = maize/soybean rotation, MBSB = maize/brachiaria/soybean/brachiaria rotation, HI = high input of fertilizers, and NV = native Cerrado vegetation. Threshold values represent optimal range for macroporosity (Reynolds et al., 2008).

significantly divergent from the other cropping systems. A strong effect of SS was observed on soil, water, and nutrient losses (Fig. 8a), and such losses were negatively correlated with soybean crop yield (Fig. 8b). Cropping systems with consorted *Brachiaria* (MBSB and MBSB-HI) positively correlated to cover rate (CR), total porosity (Tp), macroporosity (Ma), and air capacity (AC). Likewise, they also negatively correlated to Bd and relative field capacity (RFC); *i.e.* lower values of Bd and RFC (Fig. 8b). Thus, PCA shows that the relation between attributes and yield differs according to the crop, with soil properties associated to total porosity (aeration) having a positive effect especially for maize. Meanwhile, properties related to water availability have a positive effect on soybean yield: PAWC had a positive effect, and water losses (WL) a negative effect.

The computed correlations showed the strong effect of soil cover rate (CR) on water and soil losses due to erosion processes (Fig. 8b). Negative correlations were observed between CR with water, soil, and nutrient losses. Likewise, crop yield also negatively correlated with water, soil, and nutrient losses; thus, increased environmental degradation results in reduced agronomic efficiency. Moreover, soil organic carbon (OC) content was positively correlated with PAWC; *i.e.,* increased OC content promotes water availability for plant. Nevertheless, there were no significant differences for OC and PAWC among cropping systems (Table 3). Regarding aggregate stability, the indices used (GMD, MWD, and WSA) did not show any effect —no significant correlation with any attribute— after 4 years of NT-based treatments.

4. Discussion

4.1. Soil physical quality

Regarding soil structural quality, the porosity attributes showed differences among cropping systems mainly in the surface layer (Fig. 4, Table 3). These results are likely explained by the initial effects after adoption of NT-based systems, in which the differences in each system performance is a function of plant residues accumulation on the surface and the intensity of soil compaction in the upper soil layer (0–10 cm) (Blanco-Canqui & Ruis, 2018). Nevertheless, the static porosity-derived indicators did not showed values to be considered as restrictive to plant growth (Reynolds et al., 2008).

Management systems with intercropped *Brachiaria* (MBSB) evinced greater macroporosity (Ma) and air capacity (AC), along with lower relative field capacity (RFC) as compared to MS-HI in the surface layer. Such effects concur with other authors (Anghinoni et al., 2019; Moreira et al., 2016), and it can be associated to the vigorous root system of this grass. Radicular systems renewal —of each crop and *Brachiaria*'s own root system— developed new pores (biopores), which normally are classified as macropores, persisting over time (Betioli Júnior et al., 2012; Calonego et al., 2017).

Table 3
Bulk density (Bd), plant available water capacity (PAWC), air capacity (AC), and relative field capacity (RFC), Geometric mean diameter (GMD), mean weight diameter (MWD), water stable aggregates (WSA), and organic carbon (OC) of each treatment at two soil depths. Data from 2015 represents the initial condition of the experiment and the error bar represents standard error.

Soil Management System	Year	Depth (m) 0–0.05			
		Bd (Mg m^{-3})	PAWC (m^3 m^{-3})	AC (m^3 m^{-3})	RFC
SS	2015	1.06 ± 0.04	0.13 ± 0.004	0.20 ± 0.03	0.66 ± 0.04
MM		1.01 ± 0.02	0.12 ± 0.004	0.25 ± 0.01	0.63 ± 0.01
MS		0.94 ± 0.02	0.14 ± 0.003	0.22 ± 0.01	0.64 ± 0.01
MBSB		1.02 ± 0.04	0.13 ± 0.004	0.18 ± 0.03	0.69 ± 0.04
MBSB-HI		0.96 ± 0.04	0.12 ± 0.006	0.24 ± 0.01	0.58 ± 0.02
MS-HI		0.94 ± 0.07	0.15 ± 0.012	0.22 ± 0.04	0.61 ± 0.05
SS	2018	1.06 ^{ns}	0.09 ^{ns}	0.18 AB	0.69 AB
MM		1.10 ^{ns}	0.11 ^{ns}	0.13 AB	0.76 AB
MS		1.10 ^{ns}	0.10 ^{ns}	0.15 AB	0.73 AB
MBSB		1.01 ^{ns}	0.11 ^{ns}	0.24 A	0.62 B
MBSB-HI		1.07 ^{ns}	0.10 ^{ns}	0.20 AB	0.67 AB
MS-HI		1.13 ^{ns}	0.13 ^{ns}	0.11 B	0.80 A
		0.15–0.20 Bd (Mg m^{-3})	PAWC (m^3 m^{-3})	AC (m^3 m^{-3})	RFC
SS	2015	1.11 ± 0.03	0.12 ± 0.004	0.16 ± 0.02	0.72 ± 0.03
MM		1.04 ± 0.01	0.11 ± 0.002	0.19 ± 0.01	0.67 ± 0.01
MS		1.05 ± 0.06	0.13 ± 0.007	0.16 ± 0.02	0.72 ± 0.03
MBSB		1.06 ± 0.02	0.13 ± 0.012	0.15 ± 0.03	0.74 ± 0.05
MBSB-HI		1.03 ± 0.01	0.13 ± 0.011	0.17 ± 0.03	0.70 ± 0.05
MS-HI		0.96 ± 0.03	0.14 ± 0.007	0.23 ± 0.01	0.62 ± 0.02
SS	2018	1.13 ^{ns}	0.11 ^{ns}	0.15 ^{ns}	0.73 ^{ns}
MM		1.04 ^{ns}	0.11 ^{ns}	0.18 ^{ns}	0.68 ^{ns}
MS		1.12 ^{ns}	0.13 ^{ns}	0.15 ^{ns}	0.73 ^{ns}
MBSB		1.12 ^{ns}	0.13 ^{ns}	0.13 ^{ns}	0.77 ^{ns}
MBSB-HI		1.06 ^{ns}	0.12 ^{ns}	0.17 ^{ns}	0.71 ^{ns}
MS-HI		1.11 ^{ns}	0.10 ^{ns}	0.16 ^{ns}	0.72 ^{ns}
		0–0.20 GMD (mm)	MWD (mm)	WSA (%)	OC (g kg^{-1})
SS	2018	4.55 ^{ns}	4.83 ^{ns}	95.50 ^{ns}	15.60 ^{ns}
MM		4.18 ^{ns}	4.62 ^{ns}	94.80 ^{ns}	16.80 ^{ns}
MS		4.65 ^{ns}	4.86 ^{ns}	96.90 ^{ns}	15.90 ^{ns}
MBSB		4.31 ^{ns}	4.70 ^{ns}	95.20 ^{ns}	14.70 ^{ns}
MBSB-HI		4.30 ^{ns}	4.72 ^{ns}	92.70 ^{ns}	16.30 ^{ns}
MS-HI		4.39 ^{ns}	4.73 ^{ns}	96.00 ^{ns}	16.10 ^{ns}

Means in 2018 followed by different letters differ by Tukey's test ($p < 0.05$)
ns = not significant. SS = soybean monoculture, MM = maize monoculture, MS = maize/soybean rotation, MBSB = maize/brachiaria/soybean/brachiaria rotation, and HI = high input of fertilizers.

Nevertheless, we pointed out that only slight numerical differences were computed regarding the *Brachiaria* effects on soil physical quality. Moreover, all cropping systems in 2018 had values close to or within the optimal range ($0.16 < AC<0.22$ and $0.6 < RFC<0.7$) as proposed by Reynolds et al. (2008), except for MS-HI which showed low AC (0.11) and high RFC (0.80), differing statistically from MBSB in the top soil layer (Table 3). These observed physical properties in the MS-HI area (low AC and high RFC) are possibly warning us on incipient soil compaction due to machinery traffic.

Despite significant differences not being computed regarding aggregate stability nor soil organic carbon content (Table 3), our results provided valuable insights about how cropping systems with crop diversification can contribute to improving or maintaining soil structural quality (Anghinoni et al., 2019; Kassam et al., 2018). It is important to note that effects on aggregate stability on Oxisols are less expected due to their natural high aggregate stability (immanent granular structure) (Ferreira et al., 1999). Furthermore, it would be expected for soils under NT-based management systems to exhibit gradual improvements over time (Moraes et al., 2016; Reichert et al., 2016); thus, the importance of long-term NT systems that prioritize straw production and soil

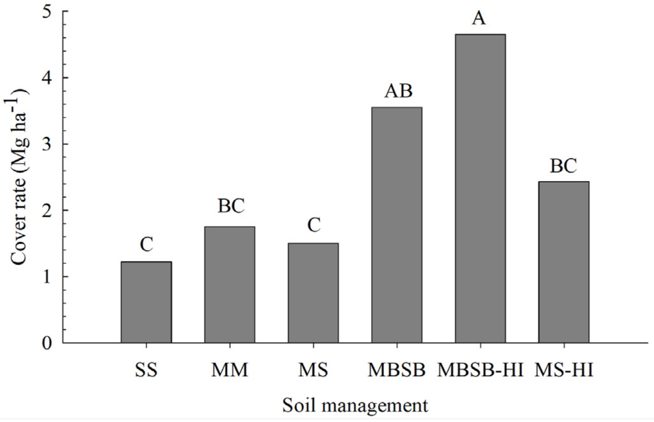

Fig. 5. Soil cover rate for each treatment at harvest in the 2018–2019 crop season. Means followed by different letters differ by Tukey's test ($p < 0.05$). SS = soybean monoculture, MM = maize monoculture, MS = maize/soybean rotation, MBSB = maize/brachiaria/soybean/brachiaria rotation, and HI = high input of fertilizers.

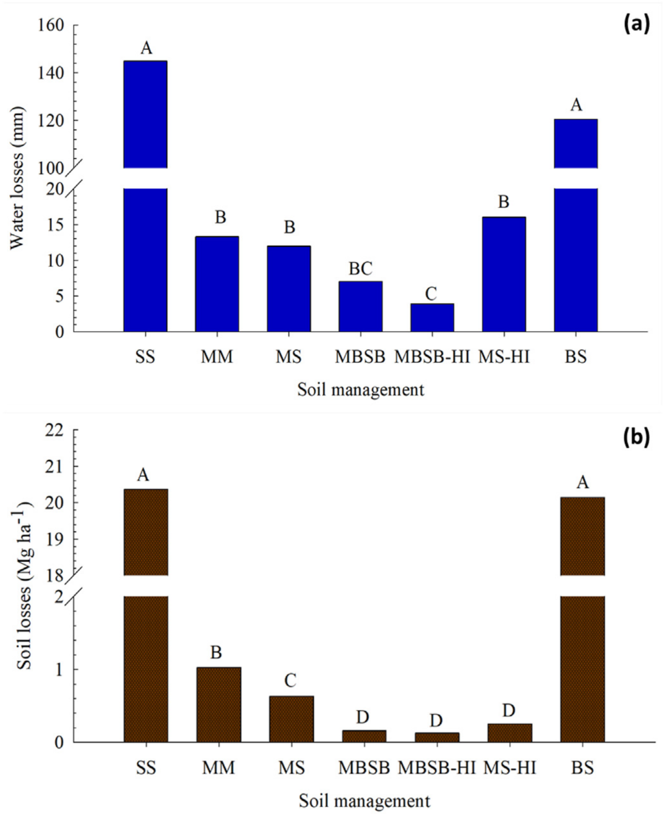

Fig. 6. Water losses by runoff (a) and soil losses by water erosion (b) for each treatment in the 2018–2019 crop season, corrected to 9% slope. Generalized least squares were used due to heteroscedasticity. Means followed by different letters differ by Tukey's test ($p < 0.05$). SS = soybean monoculture, MM = maize monoculture, MS = maize/soybean rotation, MBSB = maize/brachiaria/soybean/brachiaria rotation, BS = bare soil, and HI = high input of fertilizers.

cover (*e.g.*, crop rotation and consorted grasses) to promote increases of soil OC contents (Gonzalez, 2018). Nevertheless, NT-based systems are extremely dependent on the local physical and climatic characteristics (Pittelkow et al., 2015), and our area of study is located in a tropical region, where climate conditions favor rapid degradation of organic matter, impeding its accumulation as soil cover (Six et al., 2002). In this regard, monocultural systems promoted minimum biological conditions for accumulation of OC content or improvement of aggregate stability. Conversely, systems with plant species diversification and high investment in fertilization, MBSB, MBSB-HI or MS-HI, are likely to promote and increase the accumulation of OC over time since the main controlling mechanisms of OC content are soil fertility management and crop rotation intensification (Ferreira et al., 2018).

Macroporosity and soil bulk density of the cropping systems corresponded to good soil physical quality, since these results were within the favorable limits established by Reynolds et al. (2008) and Severiano et al. (2011). This may be due to the nature of the Oxisols (granular structure), which intrinsically correspond to almost null physical restrictions to plant development, except for low available water capacity (Ferreira et al., 1999; Silva et al., 2015). Thus, considering how resilient Oxisols are, four years under NT-systems was not enough to show evidence of soil physical degradation in any treatment (*e.g.*, increased bulk density, and low macroporosity). Oxisols —although very clayey— are excessively drained due to its granular structure, a reflex of the gibbsitic mineralogy, which implies physical resilience to soil degradation as shown by Bonetti et al. (2017). Nevertheless, punctual improvements were observed, such as an increase in soil aeration due to crop rotation intensification. This corresponded to higher air capacity (AC) and macroporosity (Ma) in MBSB as compared to MS-HI. This is likely a positive impact of consorted *Brachiaria* in cropping systems. Grasses like *Brachiaria* can lead to a series of physical benefits such as formation of biopores due to the activity of their vigorous root system (Betioli Júnior et al., 2012; Calonego et al.,

Table 4
Nutrient losses by sediment erosion, runoff, and total amount lost for each treatment in the 2018–2019 crop season. Generalized least squares were used due to heteroscedasticity.

Soil Management System	K	P	Ca	Mg	S	Zn	Fe	Cu	Mn
	(kg ha^{-1})								
Nutrients in runoff									
SS	4.076 A	0.372 A	3.641 B	1.252 B	0.372 ABC	0.039 ^{ns}	9.852 A	0.004 AB	0.084 B
MM	0.123 C	0.022 BCD	0.171 D	0.060 DE	0.003 C	0.002	0.855 BC	0.001 B	0.004 CD
MS	0.147 C	0.026 C	0.167 D	0.065 D	0.017 C	0.003	0.856 B	<0.001 B	0.003 CD
MBSB	0.171 C	0.013 CD	0.157 D	0.051 DE	0.028 C	0.002	0.240 BC	<0.001 B	0.003 CD
MBSB-HI	0.096 C	0.012 D	0.109 D	0.031 E	0.024 C	0.001	0.070 C	<0.001 B	0.001 D
MS-HI	0.997 B	0.064 B	0.634 C	0.235 C	0.148 B	0.002	0.480 B	<0.001 B	0.008 C
BS	4.827 A	0.591 A	7.334 A	2.515 A	0.362 A	0.033	12.378 A	0.012 A	0.181 A
Nutrients in sediment									
SS	3.081 A	0.306 B	19.934 A	3.374 A	0.122 A	1.231 A	0.985 A	0.009 ABC	0.784 A
MM	0.107 B	0.041 CD	0.906 B	0.146 B	0.005 B	0.076 B	0.049 B	0.001 B	0.054 B
MS	0.091 BC	0.034 C	0.706 B	0.140 B	0.005 B	0.125 B	0.029 BC	0.001 B	0.061 B
MBSB	0.027 CD	0.002 D	0.138 C	0.024 C	0.001 C	0.006 C	0.007 D	<0.001 C	0.008 C
MBSB-HI	0.016 D	0.002 D	0.119 C	0.021 C	0.001 C	0.005 C	0.005 D	<0.001 C	0.008 C
MS-HI	0.089 BC	0.003 D	0.243 C	0.034 C	0.004 BC	0.010 C	0.012 CD	<0.001 C	0.011 C
BS	2.212 A	0.941 A	22.706 A	3.948 A	0.108 A	2.723 A	1.222 A	0.012 A	1.419 AB
Total nutrient loss									
SS	7.158 A	0.839 A	23.574 A	4.625 A	0.494 AB	1.270 A	10.837 A	0.013 AB	0.868 A
MM	0.231 CD	0.063 BC	1.077 B	0.207 BC	0.008 C	0.078 B	0.904 BC	0.001 B	0.057 B
MS	0.238 C	0.059 B	0.873 B	0.205 BC	0.022 C	0.128 B	0.885 B	<0.001 B	0.063 B
MBSB	0.198 CD	0.015 CD	0.295 C	0.075 CD	0.029 C	0.008 C	0.247 BC	<0.001 B	0.010 C
MBSB-HI	0.112 D	0.014 D	0.228 C	0.052 D	0.025 C	0.006 C	0.076 C	<0.001 B	0.009 C
MS-HI	1.085 B	0.067 B	0.877 B	0.269 B	0.152 B	0.012 C	0.492 B	<0.001 B	0.019 C
BS	7.039 A	1.351 A	30.041 A	6.423 A	0.470 A	2.764 A	13.601 A	0.023 A	1.599 A

Means followed by different letters differ by Tukey's test ($p < 0.05$)
ns = not significant. SS = soybean monoculture, MM = maize monoculture, MS = maize/soybean rotation, MBSB = maize/brachiaria/soybean/brachiaria rotation, BS = bare soil, and HI = high input of fertilizers.

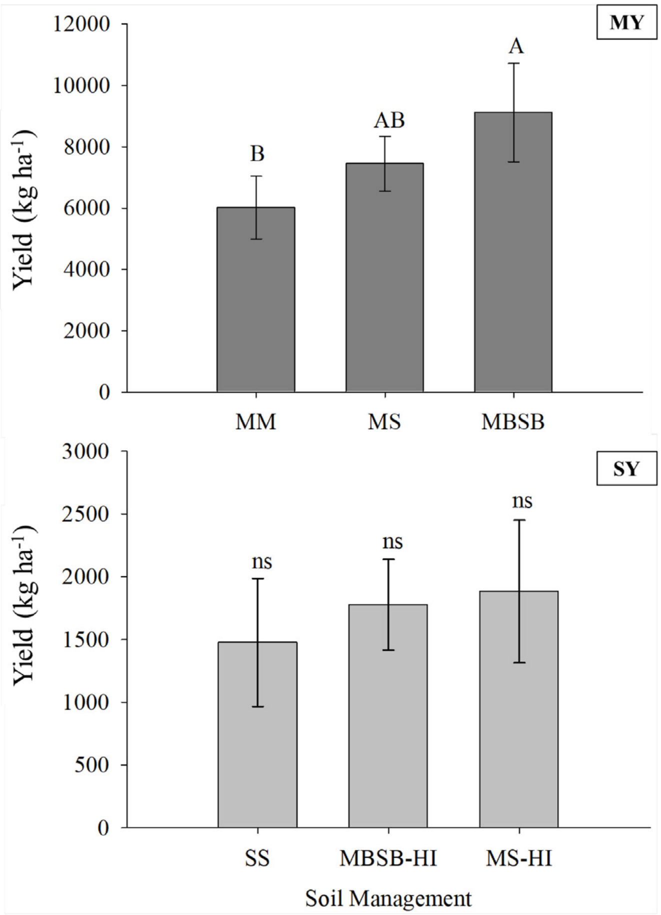

Fig. 7. Maize yield (MY) and soybean yield (SY). Error bar represents standard deviation. Means followed by different letters differ by Tukey's test ($p < 0.05$), ns = not significant. SS = soybean monoculture, MM = maize monoculture, MS = maize/soybean rotation, MBSB = maize/brachiaria/soybean/brachiaria rotation, BS = bare soil, and HI = high input of fertilizers.

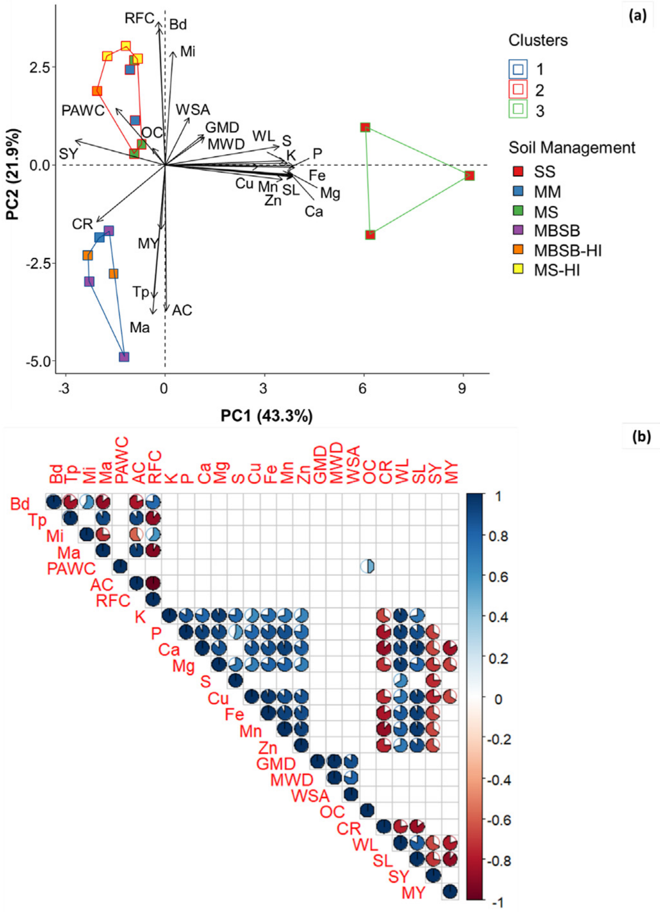

Fig. 8. Principal Component Analysis (PCA) with individuals grouped by cluster analysis (a) and matrix of Spearman correlations (b) for the soil surface layer (0–0.05 m). Only significant correlations ($p < 0.05$) are shown. RFC = relative field capacity, Bd = bulk density, Mi = microporosity, WSA = water stable aggregates, GMD = geometric mean diameter, MWD = mean weight diameter, WL = water losses, SL = soil losses, AC = air capacity, Ma = macroporosity, Tp = total porosity, MY = maize yield, CR = cover rate, SY = soybean yield, PAWC = plant available water capacity, and OC = organic carbon. SS = soybean monoculture, MM = maize monoculture, MS = maize/soybean rotation, MBSB = maize/brachiaria/soybean/brachiaria rotation, BS = bare soil, and HI = high input of fertilizers.

2017; Crusciol et al., 2014; Nascente et al., 2013; Pariz et al., 2017).

4.2. Soil cover and soil, water, and nutrient losses

Ecological intensification of cropping systems by inclusion of consorted *Brachiaria* and crop rotation reduced the negative impacts of soil erosion processes. In general, high soil cover rates (CR) (Fig. 5) corresponded to low soil and water losses (Fig. 6), especially in cropping systems applying crop rotation and consorted *Brachiaria* (MBSB and MBSB-HI). CR correlated well with the mitigation of soil erosion processes (Fig. 8b). These results are in accordance to those reported in other studies (Dechen et al., 2015; Deuschle et al., 2019; Merten et al., 2015; Zhang et al., 2015). Intercropped *Brachiaria* produced high quantity of plant biomass and remained throughout the crop season almost as perennial soil cover (Crusciol et al., 2014; Nascente et al., 2013). *Brachiaria* grasses have a high C/N ratio in their plant tissue, which reduces the decomposition rate (Timossi et al., 2007), favoring continuity of soil surface protection. Plant residues intercepts rainfall, impeding direct impact of raindrops on the soil surface, reducing surface sealing, as well as mitigating the runoff process and soil losses (Blanco-Canqui & Ruis, 2018).

Cropping systems with *Brachiaria* segregated from others by cluster analysis (Fig. 8a). The beneficial effects of intercropped *Brachiaria* on soil cover rate (CR), macroporosity (Ma), total porosity (Tp), and air capacity (AC) are possible due to its considerable production of biomass and vigorous root system (Crusciol et al., 2014). Soybean monoculture (SS) stood alone from other cropping systems (Fig. 8a), evidencing the low ecological benefits (*e.g.*, highest rates of soil, water, and nutrient losses) of this management practice and its low sustainability in this region of Minas Gerais. These results showed the vulnerability of continuous soybean systems to erosion process, with soil, water and nutrient losses only similar to those of bare soil (BS). Soybean residue has a low C/N ratio, which favors accelerated decomposition, reducing the duration of residues on the soil surface. Soybean monoculture had water losses close to 145 mm during the 2018/2019 season, which corresponds approximately to 10% of the total annual rainfall in the region. These losses are extremely severe as they can be decisive for farmers from a profitable point of view, especially considering that Oxisols are excessively drained and the region presents frequent dry spells during the rainy season. Thus, water losses can become a key limiting factor for agriculture in this region of the Brazilian Cerrado as climate changes are expected to aggravate water scarcity in regions with characteristic dry periods (IPCC, 2013). These findings can also shed light about NT management practices in other regions within the Cerrado biome to guide the soybean cultivation as hydrological conditions, such as floods and droughts, are expected to increase in duration, intensity, and frequency in future climate conditions (Rodrigues et al., 2019).

Nutrient losses from crop fields can constitute a serious expense for farmers. Regarding K, it is the nutrient with greatest losses in the area of study. Meanwhile, Brazil imports most of potassium fertilizers to meet the agricultural domestic demand (Mancuso et al., 2014; Santos et al., 2015). Phosphorus losses should be rigorously controlled since Brazilian Oxisols are naturally nutrient depleted acid soils with high fixation capacity of P (Fageria & Baligar, 2001), along with the environmental issues raised by eutrophication of water bodies due to phosphates (Withers et al., 2018). Considering the losses shown in Table 4, soybean monoculture would require replacement of ~53 kg ha^{-1} of fertilizer (NPK 08-28-16) to compensate the losses of potassium through erosion and surface runoff, which corresponds to approximately 35% of the applied fertilization during the 2018/2019 crop season.

4.3. *Crop yield*

Soybean crop yield was low compared to the mean yield for the same year in the state of Minas Gerais (~3000 kg ha^{-1}) (CONAB, 2019). Statistical analysis also indicated high sampling variability (Fig. 7). This was due partly to the reproductive period coinciding with the occurrence of an especially hot and short dry spell of 28 days between December 2018 and January 2019 —rainfall of only 3 mm during the forementioned period—. Additionally, this region of study is not a traditional soybean production area, precisely because of the edaphic and climatic conditions that pose greater risk to soybean production. Thus, results from the fifth crop season were not sensitive enough to detect possible yield differences among cropping systems. In addition to water supply deficit, the short drought period may explain the lack of an effect from greater level of investment in fertilization, possibly reducing the efficiency of the nutrient transport and plant root uptake mechanisms. Therefore, water scarcity appears to have been the primary factor in limiting soybean yield.

Based on yield results, regardless of treatments, soybean was more vulnerable than maize to the dry spell registered in the region. This greater susceptibility to water deficit is attributed to the limited root depth of soybean (Gao et al., 2010), resulting in low water uptake capacity. Regardless of the cropping system adopted, the treatments in which maize was grown in 2018/2019 had yields similar or above the mean for the same year registered in the state of Minas Gerais (~6000 kg ha^{-1}) (Conab, 2019). It is necessary to consider that, unlike soybean, the mean yield for maize in the state also includes data from low yielding areas (*e.g.,* locales with restricted suitability for maize production, or subsistence farming areas with little use of technology). Grain yield significant differences among cropping systems that cultivated maize in the 2018/2019 period (MM, MS, MBSB) corresponded to the intensification of cropping systems; *i.e.,* MBSB treatment proved to be beneficial at mid-term (after four crop seasons under NT), as compared to maize monoculture. Improvements in soil functions and abundant soil cover caused reduction of soil, water, and nutrient losses, culminating in better grain yield of MBSB as compared to MM, which was not observed concerning the comparison between monoculture and a less diversified cropping system such as MS. Thus, ecological intensification —although highly site- and weather- specific— can improve the capacity of a soil to sustain crop production, and reduce environmental degradation caused by soil erosion. These results agreed well with those reported in the literature for maize with intercropped *Brachiaria* (Borghi et al., 2012; Garcia et al., 2008).

Correlations between water, soil, and nutrient losses with crop yield showed the adverse effects of soil erosion process on crop productivity (Blanco-Canqui & Lal, 2008). Overall, soil cover rate was a key regulating factor of surface runoff, soil erosion, and nutrient losses (Fig. 8). These results indicated the superior performance of ecological intensification of cropping systems under NT, in order to promote soil and water conservation, as well as to promote nutrient stocks and increase yield potential. Species diversification also appears to have a positive association with the high investment in soil fertility, increasing soil cover and decreasing soil, water, and nutrient losses. This association is an insight that can be a starting point for future research in other regions of the world.

The positive impacts arising from ecological intensification can very well benefit farmers on the profitability of crop yields in tropical soils. Furthermore, the results are relevant towards the United Nations Sustainable Development Goals (SDGs) and the Land Degradation Neutrality, which are expected to be achieved by 2030 (Keesstra et al., 2016, 2018). Thus, our work contributes to the knowledge of soil management practices that can impact positively on soil health and food security since the soil-water system is preponderant to achieve the SDGs by 2030 (Visser et al., 2019).

5. Conclusions

In this work, we investigated whether ecological intensification of No-Till cropping systems (*i.e.,* inclusion of consorted *Brachiaria,* and crop rotation) could promote soil and water conservation in a locale within the Brazilian Cerrado (neotropical savanna), a region highly vulnerable to pronounced droughts. For this purpose, we evaluated soybean and maize monocultures, maize/soybean rotation, maize/soybean rotation with intercropped *Brachiaria*, and two levels of investment in soil fertility (medium and high) were also tested.

Results proved that soybean monoculture is a system of low sustainability —even under NT— in regions where dry spells are frequent during the rainy season. It exhibited high susceptibility to soil, water, and nutrient losses, causing low crop yields. Our results showed that water losses in soybean monoculture (SS) reached approximately 10% of the total annual rainfall. Furthermore, K losses —runoff and sediments— in SS treatment would require an additional 35% replacement of applied fertilizers. These losses accentuate the natural condition of water scarcity and seasonality in the region, and threaten (ecologically and financially) the sustainability of this cropping system. These findings can also shed light about future NT management practices —in other regions— to guide the soybean cultivation as hydrological conditions (*e.g.,* droughts) are expected to increase in duration, intensity, and frequency. Conversely, we found that ecological intensification —crop rotation and consorted *Brachiaria*— resulted in positive effects for soil and water conservation: high soil cover rate, and low soil, water and nutrient losses. Nevertheless, little effects were observed regarding different fertilizer inputs.

Finally, we observed that a 4-year period under NT cropping systems was not sufficient for full expression of significant differences on crop yields caused by ecological intensification, nevertheless significant differences between maize with crop rotation and consorted *Brachiaria* and maize monoculture were observed in a year in which an extreme dry spell occurred. Similarly, no significant effects were observed on soil aggregate stability. This was expected due to Oxisols' natural high aggregate stability —high physical resilience to soil degradation—, as well as minimum soil disturbance at NT management systems. Nevertheless, we found slight differences suggesting positive impacts of consorted *Brachiaria* on soil physical properties, such as formation of biopores and increased air capacity. These results are relevant for the improvement of cropping systems in regions with characteristic long dry season, and dry spells during the rainy season, to sustain crop production and simultaneously mitigate environmental impacts.

Declarations of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.iswcr.2021.06.006.

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