

# The effect of crop rotation and sheep grazing management on plant production and soil C and N stocks in a long-term integrated crop-livestock system in Southern Brazil

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## ABSTRACT

Integrated crop-livestock systems (ICLS) conducted under no-tillage have been shown to favour the accumulation of carbon (C) and nitrogen (N) in soil. In that systems, however, C and N accumulation in soil might depend on pasture management and the type of crop rotation used. The objective of this study was to evaluate the impact of two stocking methods (continuous and rotational) and two sheep grazing intensities (moderate and low) on winter pasture and the effect of summer crop rotation (soybean and/or maize) on crop yield and C and N stocks in an Acrisol after 14-yr under experimental conditions. The evaluated ICLS was set up for grain yield in the summer crop phase and for sheep meat production in the winter pasture phase. Pasture production, soybean and corn yield were evaluated throughout the experimental period. After 14-yr, the soil was sampled at the 0–5, 5–10, 10–20 and 20–30 cm layers to evaluate the content and stock of C and N. Higher C and N contents in soil superficial layers (0–5 and 5–10 cm) were observed under low grazing intensity in winter and soybean monoculture in summer. The C and N stocks in 0–30 cm soil layer ranged between 39 and 45 Mg C ha<sup>-1</sup> and 4 and 5 Mg N ha<sup>-1</sup>, respectively. C and N stocks in the soil were significantly related to N added through the residues of pasture and summer crop. This positive relationship is possibly explained by the higher efficiency of microbes in using crop residues enriched in N with posterior stabilization of microbial residues through organo-mineral association in the soil. The higher content and stocks of C and N associated with low intensity grazing favoured a higher maize yield (40%) compared to moderate grazing intensity in the 2015/2016 season. According to our results, the accumulation of C and N in the soil under ICLS involving low grazing intensity in the winter and soybean monoculture in the summer was related to the N added/recycled by the soybean and by the hibernal pasture.

## 1. Introduction

Soil organic matter (SOM) influences the chemical, physical and biological conditions in the soil as well as determining its productive capacity (Lal, 2004; Ghosh et al., 2010). The SOM content is affected by soil management, especially no-tillage, and crop systems with high input of plant residues have been shown as strategies to favour SOM accumulation (Bayer et al., 2006; Veloso et al., 2018). In addition to

quantity, the residues with better quality (greater N content) may result in a greater efficiency of substrate use by the microbiota and contributing to accumulation of C and N in the soil (Cotrufo et al., 2013, 2015).

Integrated crop-livestock systems (ICLS) are defined as systems in which there is temporary alternation or rotation of pastures and crops in the same area over time (Moraes et al., 2014), contributing to the accumulation of C and N in the soil (Sá et al., 2017; Luz et al., 2019). C

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and N accumulation is dependent on the stocking method, grazing intensity in the pasture phase and on the choice of summer crops (Carvalho et al., 2010). Results have highlighted the importance of the intensity and the method of animal grazing during hibernal grazing on the accumulation of SOM, which is largely related to the impact of grazing intensity on root system development (Reeder and Schuman, 2002). However, there is a lack of information regarding the impact of ICLS with different production management systems on soil C and N stocks in subtropical environments.

Among the commercial crops utilized during summer in the subtropics, soybean stands out for its large cultivated area, currently estimated at 35.8 million hectares in Brazil, of which 11.9 million are cultivated in three southern states (Paraná, Santa Catarina and Rio Grande do Sul) (CONAB, 2019). Soybean residue has low C/N ratio, that in turn, may increase N availability due to lower soil immobilization by microorganisms and, therefore, favour the development of pasture after soybeans (Campos, 2015). On the other hand, the insertion of maize into crop rotation with soybeans propitiate a greater quantity of plant residues but with a lower quality (higher C/N ratio) compared to soybeans alone (Chen et al., 2018). In subtropical Brazil, maize cultivation is less attractive for local farmers due to the frequent occurrence of water deficits that impact more strongly maize yield, due to its higher sensitivity to water deficit mainly at the flowering stage compared to soybeans (Steduto and Raes, 2012).

Thus, there is a need for results on the impact of the stocking method, grazing intensity in the pasture phase and the crops growing in the cropping phase on soil C and N stocks and the crops yield. Therefore, this study was aimed to evaluate the impact of grazing (stocking method and grazing intensity) in hibernal pasture and cash crops (monoculture of soybean, and crop rotation of soybean and maize) in the cropping phase on soil C and N stocks, pasture production, soybean and maize yield in the Brazilian subtropics. The study was conducted over 14-year in an ICLS with grain and sheep-meat production in an Acrisol in the Brazilian subtropics.

## 2. Material and methods

### 2.1. Description of the experiment

A long-term study was conducted using an ICLS implanted in 2003, in Experimental Agronomic Station of the Federal University of Rio Grande do Sul, in Eldorado do Sul county, Rio Grande do Sul state, Brazil (latitude 30°05'S, longitude 51°39'O, altitude 46 m). The local climate is classified as subtropical humid (Cfa) according to the Köppen classification (Kottek et al., 2006). Mean annual rainfall over the 14-yr experimental period ranged between 1200 and 2000 mm, with a mean annual temperature of 19 °C.

The soil was classified as a sandy clay loam Acrisol (FAO, 2006). At the beginning of the experiment, the 0–10 cm soil layer presented organic C content of 17 g kg<sup>-1</sup>, pH-water (1:1 soil/water ratio) of 5.3; exchangeable aluminium (Al), calcium (Ca) and magnesium (Mg) (KCl 1.0 mol L<sup>-1</sup>) of 0.3, 2.2 and 1.2 cmol<sub>c</sub> kg<sup>-1</sup>, respectively; available phosphorus (P) and potassium (K) (Mehlich 1) of 10 and 135 mg kg<sup>-1</sup>, respectively; base and Al saturation of 51% and 8%, respectively.

Prior to the experiment, the area was natural grassland of the Pampa Biome, with exotic species in the winter, such as ryegrass (*Lolium multiflorum*). The grassland was desiccated with glyphosate herbicide and limestone was applied (1.0 Mg ha<sup>-1</sup>) to raise soil pH (in water) in the 0–10 cm soil layer to 6.0.

At the beginning of the experimental period, the soil was fertilized with 18 kg ha<sup>-1</sup> of P and 33 kg ha<sup>-1</sup> of K, which is the amount of fertilizer needed for an expected soybean yield of 3.0 Mg ha<sup>-1</sup> (CFS-RS/SC, 1995; CQFS-RS/SC, 2004). Almost every year, ryegrass was sown at a density of 32 kg ha<sup>-1</sup> in the autumn-winter period and fertilized with nitrogen split in two applications, of 150 kg ha<sup>-1</sup> of N as urea.

The experimental area of 4.5 ha was divided into 16 experimental

units, varying from 0.23 to 0.32 ha per unit. The experiment was designed as randomized blocks, with four repetitions, in a 2 × 2 factorial system with subdivided plots. The main factors were two different grazing intensities (moderate and low) and two stocking methods (continuous and rotational), with subdivided plots representing two summer growing systems (soybean monoculture - soybean/soybean and crop rotation - soybean/maize).

During the pasture phase, the area was grazed by 11 month-old sheep weighing 35 ± 4 kg. A variable number of sheep were used following the *put-and-take* technique (Mott and Lucas, 1952) to maintain the recommended grazing intensities. Grazing intensities were defined by forage supply, expressed in kg of dry matter (DM) per 100 kg of live weight (LW) per day: (i) moderate grazing intensity – forage offer equivalent to 2.5 times the forage intake potential of sheep; (ii) low grazing intensity – forage offer equivalent to 5.0 times the forage of sheep potential intake. The forage intake potential of lambs according to the National Research Council (1985) is 4.0%, based on DM, low offer equivalent to 10% of the LW and moderate offer of 20% of the LW.

The two stocking methods differed by the amount of time the sheep were present in each plot. In the continuous stocking method, the sheep remained in the area during the whole grazing period, while in the rotational, the plots were subdivided and the sheep were rotated, remaining approximately two days in each pasture range. This period was calculated in function of live ryegrass leaves and accumulated degree days.

Grass length was monitored every fifteen days using a graduated *sward stick* (Barthram, 1985) with 30 random points measured per experimental unit during each pasture cycle, from 2003 to 2008. After 2008, 150 random points were measured randomly to allow better estimates. Different load adjustment was adopted to maintain a forage supply of 2.5 and 5.0 times the consumption potential. At the end of each pasture cycle, the sheep were removed, and the pasture desiccated with *glyphosate* herbicide in preparation for the subsequent summer sowing. The average annual fertilization applied during the 14-yr experimental period was 150 kg N ha<sup>-1</sup>, 30 kg P ha<sup>-1</sup> and 50 kg K ha<sup>-1</sup>, fertilized during the pasture cycle. The season and annual fertilization rates can be found in Alves et al. (2019). The maize was fertilized with rates of 110 and 150 kg N ha<sup>-1</sup>, respectively, only in 2009/2010 and 2011/2012 growing seasons.

In the cropping phase, each plot was divided into two subplots. Each subplot was divided in two crop systems: monoculture - soybean/soybean and crop rotation - soybean/maize (50%-50%), both under no-tillage. In the first summer cycle, soybean (*Glycine max*) was sown in the whole experimental area. In the second cycle, soybean was sown in half the subplot and maize in the other half (subplots monoculture and crop rotation, respectively), with 45 cm between lines and a population of 280,000 plants ha<sup>-1</sup>. Soybean and maize were sown from October to November.

### 2.2. Crop yield

Soybean yield was evaluated over five crop/growing seasons (2003/2004, 2004/2005, 2006/2007, 2010/2011 and 2014/2015). The maize yield was evaluated over six crop/growing seasons (2005/2006, 2007/2008, 2009/2010, 2011/2012, 2013/2014 and 2015/2016).

Yield was evaluated by collecting from five random points in each subplot, each point with two linear meters, totalling 4.5 m<sup>2</sup>. After collection, the samples were dried and the grain yield presented 130 g kg<sup>-1</sup> of moisture content.

### 2.3. The water requirement satisfaction index (WRSI) of the soybean and maize crops

WRSI was calculated from the ratio between real (ET<sub>r</sub>) and maximum evapotranspiration (ET<sub>m</sub>) of the crop (soybean or maize). When water requirement and supply meet, the WRSI is equal to 1 (ET<sub>r</sub> =

ETm). When the  $ETr < ETm$ , the crop yield may be limited by deficit water stress. The WRSI was calculated for all years from October 15 to March 15, including the period from sowing to harvesting of the summer crops (soybeans and corn) (Fig. S1). For the correlation study between WRSI and crop yield, the reproductive period (stages R1-R6) was used as this period is critical for a good crop yield (Franchini et al., 2012).

The values of  $ETr$  and  $ETm$  were determined for the soybean and maize crop cycle. The BIPZON model was used to simulate the crop hydric balance (Forest, 1984). This model allows the input of data from converging variables such as climate (rainfall and average daily temperature); crop (coefficient of the crop  $Kc$ ); and soil (available water capacity). The available water capacity was estimated for the first 50 cm of soil, considering an effective root depth of 60 mm.

#### 2.4. Determination of forage production

Above-ground productivity (AGP,  $Mg\ ha^{-1}$ ) of the pasture was evaluated in the years 2004, 2005, 2006, 2007, 2010, 2011, 2012, 2015 and 2016. The AGP was calculated by using the accumulated forage mass at the beginning of the grazing period, added to the forage accumulation rate ( $kg\ day^{-1}$ ) and multiplied by the number of grazing days, over an average period of  $101 \pm 9$  days.

Residual aboveground forage mass (RFM,  $Mg\ ha^{-1}$ ) was calculated at the end of the grazing period in the years 2010, 2011, 2012, 2015 and 2016, using subsamples. Samples were collected randomly using a  $0.25\ m^2$  metal frame ( $0.5 \times 0.5\ m$ ). All the remaining above ground forage, was cut and dried in an oven with air circulation at  $65\ ^\circ C$  for 72 h. After drying, the material was weighed and the results expressed as  $Mg\ ha^{-1}$ .

#### 2.5. Soil sampling and analyses of the C and N content of the soil

Soil was sampled with an auger at the layers 0–5, 5–10, 10–20 and 20–30 cm. The samples were dried in a forced-air oven at  $45\ ^\circ C$ . The larger lumps broken up, ground and sieved with a 2.0 mm sieve. A 2.0 g subsample was ground and sieved to  $\leq 0.100\ mm$ . Soil C and N contents were analysed by dry combustion in a Fisher Scientific FlashEA®. Bulk density was measured using the volumetric ring method (Blake and Hartge, 1986), in the 0–10, 10–20 and 20–30 cm layers. Then, the C and N stocks in the 0–30 cm layer were calculated by equivalent soil mass method (Ellert and Bettany, 1995). The soil used as the reference was

sampled from the treatment with moderate grazing intensity under the continuous stocking method and soybean monoculture. Soil density in the 0–10 cm layer was used in the calculation of the C and N stocks in the 0–5 and 5–10 cm layers.

Soil C accumulation rates were calculated as the difference between the soil C stock of the treatments and the reference system with the lowest C stock (crop rotation, moderate grazing intensity and continuous stocking method), divided by the time elapsed since the implementation of the experiment (14-yr).

#### 2.6. Statistical analyses

Statistical analysis was performed with SAS® 9.4 software and the results were subjected to a normality analysis by the Shapiro-Wilk test and the homogeneity of variances by the Levene test, both at a significance level of 5%. The results were submitted to ANOVA at a 5% significance level (ANOVA,  $P > 0.05$ ). When significant, the difference between the treatment means was evaluated by the Tukey test, also at 5%.

A factorial model with split plots was used for the analysis of soybean yield and RFM. The effects were two stocking methods and two grazing intensities, with the cropping systems subdivided in plots, considering the effects of the block (B), the stocking method (M), grazing intensity (I), cropping system (S), the interactions  $M^*I$ ,  $M^*S$ ,  $I^*S$ ,  $M^*I^*S$  and the year as a repeated measure of time. A factorial model was used for the analysis of maize yield and AGP, considering the B, M, I effects and the  $M^*I$  interaction, and the year as a repeated measure of time. The factorial model used subdivided sub-plots for the C and N content in the soil, with the soil layer as the subdivided sub-plot, considering the effects B, M, I, S, soil layer (C) and the interaction between  $M^*I$ ,  $M^*S$ ,  $I^*S$ ,  $M^*I^*S$ ,  $M^*C$ ,  $I^*C$ ,  $S^*C$ ,  $M^*I^*C$ ,  $M^*S^*C$ ,  $I^*S^*C$  and  $M^*I^*S^*C$ . For the stocks and the accumulation rates of C and N in the soil, considering the effects B, M, I, S and the interaction between  $M^*I$ ,  $M^*S$ ,  $I^*S$  and  $M^*I^*S$ . In all models, the B effect and its interactions were considered random effects and the other factors were considered fixed effects.

The significance of the relationship between C and N content in the soil and C and N inputs by crops and/or pasture was evaluated using Pearson's correlation coefficients ( $r$ ) at the 5% level.

**Table 1**

Analysis of variance of stocking methods (S), grazing intensity (G), summer cropping systems (C), years (Y), soil layer (L) and their effect on crop and forage parameters [soybean and maize grain yield, net primary production (NPP) and residual forage mass (RFM) of winter pasture] over the years and on soil parameters [content of C and N, stock of C and N, and annual C and N accumulation rate (C and N-rate)] in an Acrisol subjected to different winter pasture methods and intensities and summer cropping systems in a 14-yr long-term integrated crop-livestock system in Southern Brazil.

Effect	Crop and forage parameters				Effect	Soil parameters					
	Soybean	Maize	NPP	RFM		C content	N content	C stock	N stock	C-rate	N-rate
S	**	ns	ns	ns	S	ns	ns	ns	ns	ns	ns
G	***	*	**	**	G	**	*	**	ns	**	**
C	ns	–	–	*	C	*	**	*	**	**	**
Y	***	***	***	***	L	***	***	–	–	–	–
S × G	**	ns	ns	ns	S × G	ns	ns	ns	ns	ns	ns
S × C	ns	–	–	ns	S × C	ns	ns	ns	ns	ns	ns
S × Y	***	ns	ns	ns	S × L	ns	ns	–	–	–	–
G × C	ns	–	–	ns	G × C	ns	ns	ns	ns	ns	ns
G × Y	ns	***	ns	ns	G × L	**	*	–	–	–	–
C × Y	ns	–	–	ns	C × L	**	*	–	–	–	–
S × G × C	ns	–	–	ns	S × G × C	ns	ns	ns	ns	ns	ns
S × G × Y	**	ns	ns	ns	S × G × L	ns	ns	–	–	–	–
S × C × Y	ns	–	–	ns	S × C × L	ns	ns	–	–	–	–
G × C × Y	ns	–	–	ns	G × C × L	ns	ns	–	–	–	–
S × G × C × Y	ns	–	–	ns	S × G × C × L	ns	ns	–	–	–	–

\*Significant at  $P < 0.05$ ; \*\* Significant at  $P < 0.01$ ; \*\*\* Significant at  $P < 0.001$ ; ns not significant.

**Table 2**

Soybean grain yield in an integrated crop-livestock system under different stocking methods (continuous and rotational) and grazing intensities (moderate and low) in five years in Southern Brazil.

Year	Continuous		Rotational	
	Moderate	Low	Moderate	Low
	Yield (Mg ha <sup>-1</sup> )			
2003/2004	1.25 Ab	1.49 Ab	1.32 Ac	1.15 Ac
2004/2005	0.57 Cc	1.19 Bc	1.50 Ac	1.61 Ab
2006/2007	0.81 Ac	0.93 Ac	0.87 Ad	0.85 Ad
2010/2011	1.35 Bb	1.60 ABb	1.81 Ab	1.78 Ab
2014/2015	2.24 Ba	2.56 Ba	3.67 Aa	3.43 Aa

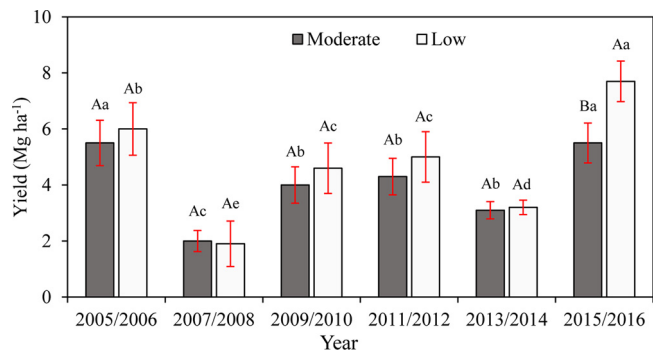
Means followed by the same upper case letters comparing treatments (continuous - moderate, continuous - low, rotational - moderate and rotational - low) in different years, and the same lower case letters comparing the years within each stocking method and grazing intensity are not significantly different by Tukey test at  $P < 0.05$ .

### 3. Results

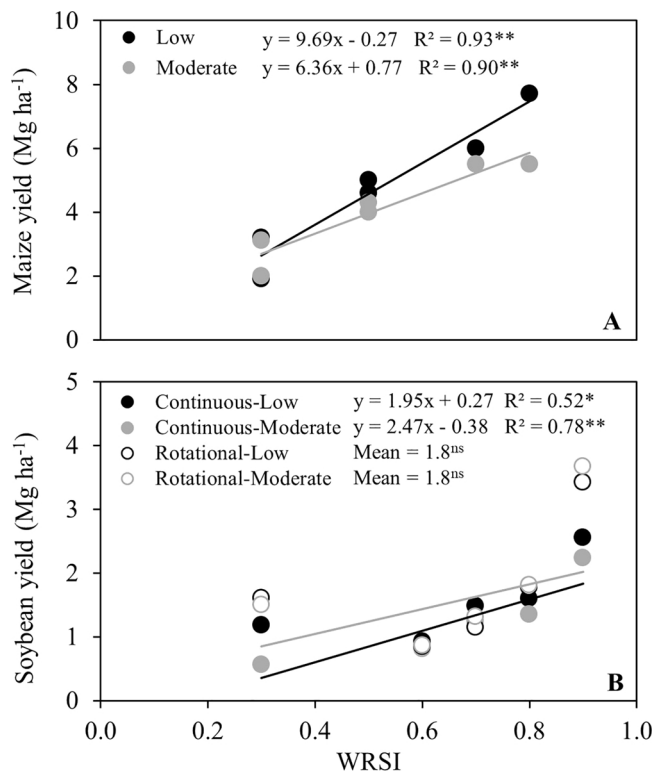
#### 3.1. Crop and forage production

Soybean yield was not affected by the cropping system (Tables 1 and 2). In two (2003/2004 and 2006/2007) of the five harvests evaluated, soybean yield was not affected by stocking method and grazing intensity. In the 2004/2005 season, the adoption of rotational stocking method, favour greater soybean yield in continuous-moderate (30%) and continuous-low (272%) (Tables 1 and 2). On the other hand, in the 2010/2011 season, lower soybean yield was observed in the continuous-moderate treatment compared to the other treatments. In the 2014/2015 season, independent of the grazing intensity, the average soybean yield observed in rotational stocking method was 48% greater than continuous stocking method (Table 2). The highest soybean yield during the experimental period was observed in the 2014/2015 season, with an average of 3.0 Mg ha<sup>-1</sup>.

Maize yield was slightly affected by stocking methods and grazing intensities. Maize yield was low throughout the evaluation period, ranging from 1.9 Mg ha<sup>-1</sup> in the 2007/2008 season to 7.7 Mg ha<sup>-1</sup> in the 2015/2016 season (Fig. 1). Although maize showed a tendency for higher yields at low grazing intensity, this result was significant only in the 2015/2016 season, which also had the highest maize yields compared to other seasons (Fig. 1). In the 2015/2016 season, grain yield in low grazing intensity was 40% higher (2.4 Mg ha<sup>-1</sup>) than in moderate intensity.



**Fig. 1.** Maize grain yield in an integrated crop-livestock system, submitted different grazing intensities (moderate and low) as mean of the stocking methods, in six years (2005, 2007, 2009, 2011, 2013 and 2015) in Southern Brazil. Means followed by the same upper case letters comparing grazing intensities within each year and followed by the same lower case letters comparing different years within each grazing intensity are not significantly different by the Tukey test at  $P < 0.05$ .



**Fig. 2.** Relationship between maize yield (A) and water requirement satisfaction index (WRSI) to different grazing intensities (moderate and low) and soybean yield (B) and WRSI to interaction between stocking methods (continuous and rotational) and grazing intensities (moderate and low) in 14-yr long-term integrated crop-livestock system in Southern Brazil. **\*\*** Significant at  $P < 0.01$ . **\*** Significant at  $P < 0.05$ . **ns** Not significant.

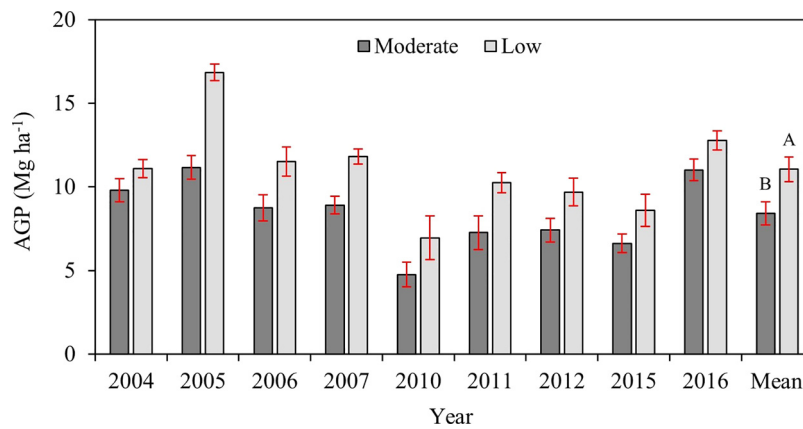
Fig. 2A presents the relationship between WRSI and maize yield under different grazing intensities (moderate and low). At low grazing intensity, for every 0.1 unit increase in WRSI, maize yield increased by 0.97 Mg ha<sup>-1</sup>, versus 0.64 Mg ha<sup>-1</sup> at moderate grazing intensity. In Fig. 2B, the relationship between WRSI and soybean yield is presented under combination of stocking method and grazing intensity: continuous-low, continuous-moderate, rotational-low and rotational-moderate. Under continuous stocking method with low grazing intensity, the increase of 0.1 unit increase in WRSI favoured the increased of soybean yield by 0.24 Mg ha<sup>-1</sup> versus 0.20 Mg ha<sup>-1</sup> under continuous stocking method with moderate grazing intensity. The relationship was not significant under rotational stocking method.

AGP ranged from 4.8–16.8 Mg ha<sup>-1</sup> and was affected by grazing intensity (Fig. 3). Over the experimental period, AGP in low intensity grazing (11.1 Mg ha<sup>-1</sup>) was 32% higher than in moderate grazing intensity (8.4 Mg ha<sup>-1</sup>) (Fig. 3). RFM aboveground was affected by grazing intensity and cropping system over the experimental period (Table 1). RFM mean was 7% higher in soybean monoculture (3.1 Mg ha<sup>-1</sup>) than in crop rotation (2.8 Mg ha<sup>-1</sup>) (Fig. 4). Regarding grazing intensities, low grazing intensity (3.4 Mg ha<sup>-1</sup>) resulted in 28% more residue than moderate intensity (2.7 Mg ha<sup>-1</sup>) (Fig. 4).

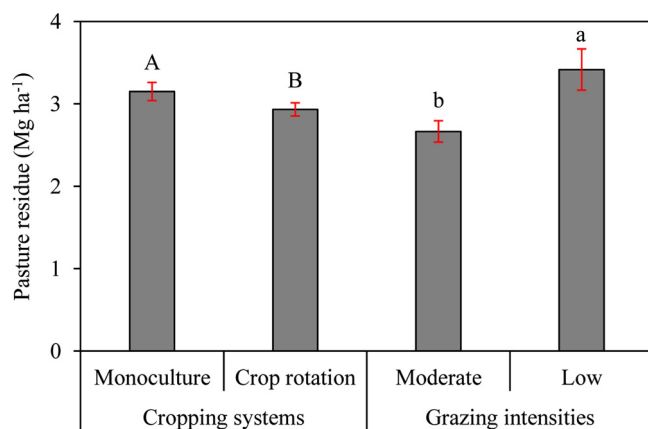
#### 3.2. Soil C and N content and stocks

C and N content in the superficial soil layers (0–5 and 5–10 cm) were affected by cropping systems, as well as grazing intensities (Table 1 and Fig. 5). In the 0–10 cm layer, the average C concentration under low grazing intensity was 20% higher (14.1 g kg<sup>-1</sup>) than under moderate grazing intensity (11.8 g kg<sup>-1</sup>) (Fig. 5B). Using the average of the two layers (0–5 and 5–10 cm), the highest N concentration were observed under low grazing intensity (1.5 g kg<sup>-1</sup>) compared to under





**Fig. 3.** Aboveground productivity (AGP) (winter ryegrass) in an integrated crop-livestock system under two grazing intensities (moderate and low), as mean of the stocking methods in Southern Brazil. Means followed by the same letters comparing grazing intensities are not significantly different by Tukey test at  $P < 0.05$ .



**Fig. 4.** Residual aboveground forage mass (RFM) (winter ryegrass) in an integrated crop-livestock system under different cropping systems (soybean monoculture and soybean-maize rotation) and grazing intensities (moderate and low) for five years in Southern Brazil. Means followed by the same upper case letters comparing cropping systems and the same lower case letters comparing grazing intensities are not significantly different by Tukey test at  $P < 0.05$ .

moderate grazing intensity ( $1.2 \text{ g kg}^{-1}$ ) (Fig. 5D). Greater C and N concentration in 0–5 and 5–10 cm soil layers was observed in soybean monoculture, averaging in the 0–10 cm layer  $14.3$  and  $1.6 \text{ g kg}^{-1}$  of C and N, respectively, which is around 22 and 27% greater than crop rotation system (Fig. 5A and C).

C and N stocks in the 0–30 cm soil layer ranged from 39 to  $45 \text{ Mg ha}^{-1}$  and 3.9 to  $4.9 \text{ Mg ha}^{-1}$ , respectively, and were affected by cropping system and grazing intensities. Higher C and N stock in 0–30 cm soil layer was observed in soybean monoculture ( $45$  and  $5 \text{ Mg ha}^{-1}$ , respectively) compared to crop rotation system ( $39$  and  $4 \text{ Mg ha}^{-1}$ , respectively) (Table 4). This led to significant accumulation rates of  $500 \text{ kg C ha}^{-1} \text{ year}^{-1}$  and  $78 \text{ kg N ha}^{-1} \text{ year}^{-1}$  in the soil under soybean monoculture (Table 4). In addition, C and N stock was 11 and 9% higher, respectively, under low grazing intensity compared to moderate grazing. Soil accumulation rates was  $500 \text{ kg C ha}^{-1} \text{ year}^{-1}$  and  $57 \text{ kg N ha}^{-1} \text{ year}^{-1}$  under low intensity and  $200 \text{ kg C ha}^{-1} \text{ year}^{-1}$  and  $27 \text{ kg N ha}^{-1} \text{ year}^{-1}$  under moderate grazing intensity (Table 4).

Significant relationships between the input of C (Fig. 6A) and N (Fig. 6B) via crop residues from each cropping system, monoculture and crop rotation, and the C stock were observed. Each 1000 kg of C annually inputted via above-ground biomass, the C stock increased by  $14.5 \text{ kg ha}^{-1}$  in soybean monoculture, versus  $4.5 \text{ kg ha}^{-1}$  in the crop rotation system. For N inputs, each 10 kg of N annually inputted via above-ground biomass, the N stock increased by  $0.53 \text{ Mg ha}^{-1}$  in

soybean monoculture, versus  $0.30 \text{ Mg ha}^{-1}$  in the crop rotation system.

#### 4. Discussion

Our study showed that low grazing intensities favour significant increases in soil C and N stocks in subtropical environments, which corroborate to previous studies (Souza et al., 2009; Assmann et al., 2014). In our study, considering the 0–30 cm soil layer, the highest rates of C and N accumulation were observed in the systems with low intensity grazing and soybean monoculture (Table 4). This higher soil accumulation is associated with higher C and N input via crop residues at low compared to moderate grazing intensity (annual difference  $2.7 \text{ Mg ha}^{-1}$ ), as demonstrated by the higher AGP (Table 3 and Fig. 3). This higher C and N input in low grazing intensity is due to lower forage intake by the lower number of sheep, leading consequently to higher AGP and RFM (Figs. 3 and 4).

Soybean monoculture promoted greater increase in soil C when compared to crop rotation. Although the relationship between soil C stock and C input was significant in both soybean monoculture and crop rotation systems (Fig. 6A), for each kg of C added annually via plant residues, there was an increase of  $14.5 \text{ kg C ha}^{-1}$  under soybean monoculture and  $4.5 \text{ kg C ha}^{-1}$  under crop rotation. In addition, N input via residues caused alterations in the soil C stocks under both cultivation systems. Each kg of N added annually via plant residues generated greater increase under soybean monoculture ( $0.53 \text{ Mg C ha}^{-1}$ ) than under crop rotation ( $0.30 \text{ Mg C ha}^{-1}$ ). (Fig. 6B). Thus, our results suggests that residue quality was the main driver for soil C accumulation, as observed by Manzoni et al. (2008), which is possibly associated to greater efficiency of microorganisms in stabilizing C from labile (higher N content) plant residue into microbial residues that later might be stabilized in organo-mineral association (Cotrufo et al., 2013, 2015, Veloso et al., 2019).

The effect of higher N supply for forage production in succession, is probably due to the high biological N fixation which is used to supply the needs of the soybean crop, therefore reducing the dependence on N from SOM mineralization (Ciampitti and Salvagioti, 2018). The higher N supply available for the subsequent pasture cultivation in soybean monoculture system is associated to both lower C/N ratio and higher N input through crop residues to the soil, favouring then higher RFM compared to maize. Varvel and Wilhelm (2003) also observed that the soybean crop could contribute larger quantities of N to subsequent crops, giving better conditions for the development of pasture in contrast to maize. In addition, the absence of N fertilization under maize (except for the 2009/2010 and 2011/2012 seasons), probably contributed to high N immobilization, negatively affecting the initial development of the successive hibernal pasture (Campos, 2015) when compared to soybean monoculture system.

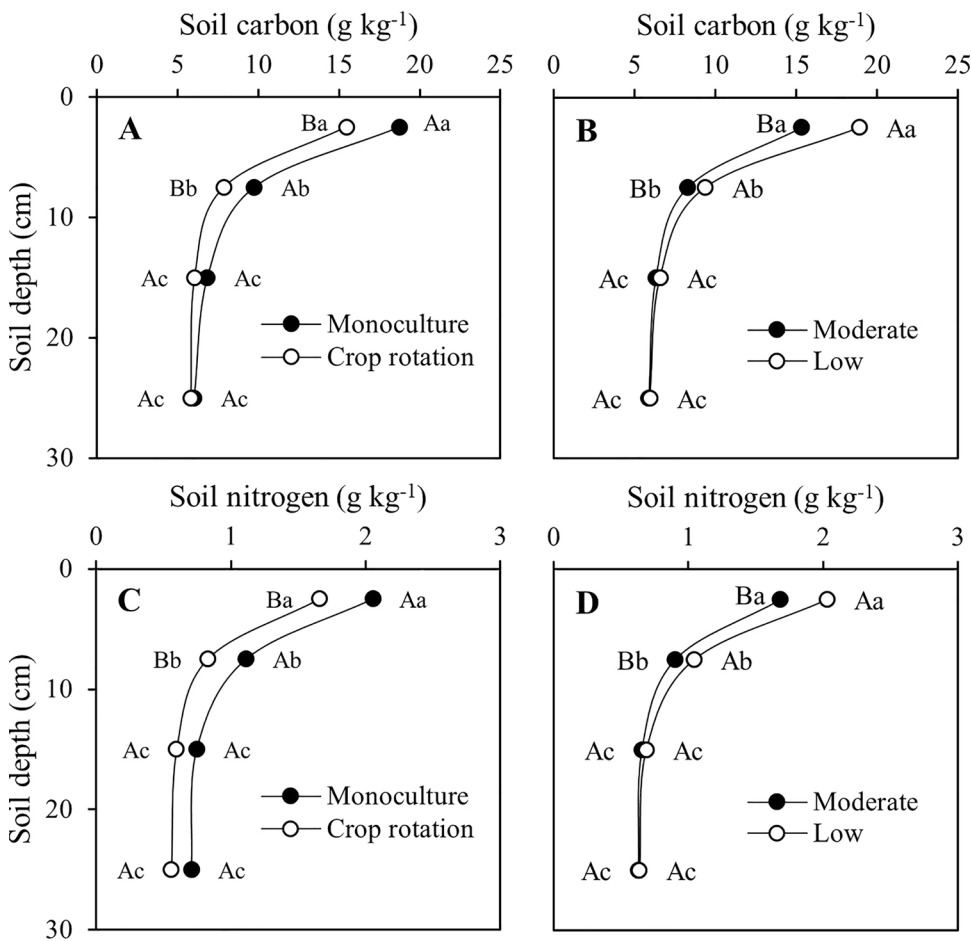


Fig. 5. Content of carbon (A and B) and nitrogen (C and D) in soil under integrated crop-livestock system under different cropping systems (soybean monoculture and soybean-maize rotation) and grazing intensities (moderate and low). Means followed by the same upper case letters comparing organic content of carbon and nitrogen contents in soil between the cropping systems and grazing intensities within each depth, and the same lower case letters comparing content of carbon and nitrogen organic carbon contents between depths for within each cropping system and grazing intensity are not significantly different by Tukey test at  $P < 0.05$ .

Mainly due to the frequent droughts (as indicated by the low WRSI observed during the majority of the crop seasons – Fig. 2), the average C input over the experimental period was  $2.4 \text{ Mg ha}^{-1}$  in the crop rotation system (Table 3), very similar to that observed in the soybean monoculture. Although maize adoption in cropping systems in subtropical environments is a viable alternative with a potential for a C input higher than  $4 \text{ Mg ha}^{-1}$  (Veloso et al., 2018), the C input by maize in this study was much lower than expected.

The greater maize grain yield after low intensity grazing in 2015/2016 season (Fig. 1) is possibly related to the higher C and N soil content in this system obtained in the long-term compared to moderate intensity grazing (Table 4). It can also be explained by the higher WRSI, which showed a linear relationship with yield (Fig. 2). Thus, the system using low grazing intensity, which had a higher capacity to supply the nutritional needs, especially N due to the larger soil stock, was more favoured under superior water supply conditions. (Fig. 2).

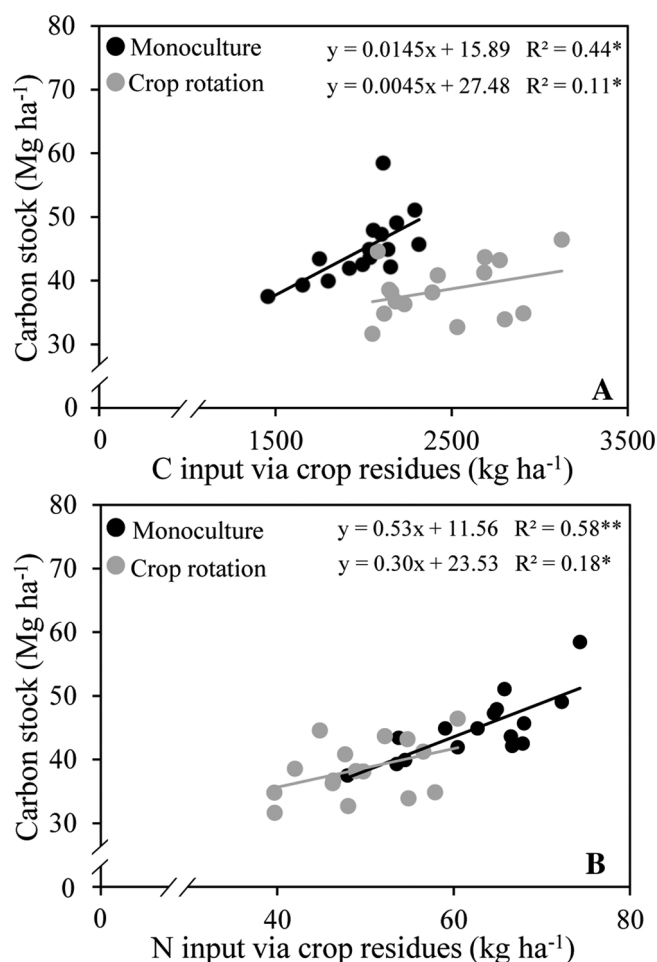
The soybean grain yield did not respond positively to increases in soil N levels caused by the adoption of low grazing intensities (Table 2). This is mainly due to the fact that the treatments in this study do not affect other chemical attributes of the soil (Alves et al., 2019) and because soybeans obtain much of their N requirement from biological N fixation, depending less of N soil supply (Ciampitti and Salvagioti, 2018) in contrast to maize. However, soybean yield was affected by the different pasture management methods and grazing intensities (Table 2). The rotational method, independent of the grazing intensity, resulted in higher soybean yield when compared to the continuous method adopted in the 2004/2005 and 2014/2015 seasons (Table 2). The higher soybean yield in the rotational stocking method can be justified by the fact that continuous grazing can affect spatial patterns of the soil attributes, increasing spatial heterogeneity of the pastures

and the environment (Laca, 2009; Auerswald et al., 2010). As the animals circulate freely selecting grazing areas, manure is deposited unevenly influencing the concentration of nutrients in the soil (McNaughton, 1985; Augustine and Frank, 2001), with the highest concentrations being found near to the rest areas, shade and water troughs (Dennis et al., 2012; Dubeux et al., 2014). This does not happen using the rotational stocking method, where the animals are placed in grazing ranges that rotate in space and time, favouring the better distribution of manure within the grazing range (Peterson and Gerrish, 1996), achieving better control of spatial nutrient cycling and soil fertility.

## 5. Conclusions

The aboveground pasture productivity and the maize yield are favored in the system with low grazing intensity during the pasture phase. In contrast, soybean presented higher yield when the rotational pasture method was used in the winter, regardless of the grazing intensity. The residual forage mass in the pasture phase was favoured by the soybean monoculture system in the summer.

Low grazing intensity in the pasture phase favoured the increase of C and N stocks in the soil. The pasture management method, continuous or rotational, did not affect the accumulation of C and N in the soil. The higher quality of soybean crop residues and similar annual input of C determined higher soil C and N stocks, in comparison to the rotation soybean/maize, suggesting an evidence that crop residues with greater N content favour soil C accumulation. Maize yield was low in most of the seasons due to the low water requirement satisfaction index, reducing the potential for the accumulation of C and N in the soil under rotation soybean/maize.



**Fig. 6.** Relationship between carbon (A) and nitrogen (B) inputs via crop residues and soil carbon stocks (0–30 cm) in different cropping systems (monoculture and crop rotation) after 14-years long-term integrated crop-livestock system in Southern Brazil. \*\* Significant at  $P < 0.01$ . \* Significant at  $P < 0.05$ .

**Table 3**

Average of annual C and N input to the soil by shoot crop residues of winter ryegrass and summer crops in an integrated crop-livestock system, under different grazing intensities (moderate and low) in winter and cropping systems (soybean monoculture and soybean/maize rotation) in summer in Southern Brazil.

Input	Cropping systems		Grazing intensity	
	Monoculture <sup>a</sup>	Crop rotation <sup>b</sup>	Moderate	Low
Winter (livestock season) contribution (kg ha <sup>-1</sup> year <sup>-1</sup> )				
C	1260	1168	1066	1364
N	19	18	16	21
Summer (crop season) contribution (kg ha <sup>-1</sup> year <sup>-1</sup> )				
C	740	1281	955	1073
N	43	31	35	39
Annual input				
C	2000	2449	2020	2437
N	62	49	51	60

<sup>a</sup> Soybean residue.

<sup>b</sup> Soybean + maize residue in summer; ryegrass residue in winter in both cropping systems.

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**Table 4**

Soil C and N stocks (0–30 cm) in an integrated crop-livestock systems with two grazing intensities (moderate and low) on winter ryegrass and two cropping systems (monoculture and crop rotation) in summer in an Acrisol in Southern Brazil.

Soil parameter	Cropping system		Grazing intensity	
	Monoculture	Crop rotation	Moderate	Low
Stocks <sup>a</sup> (Mg ha <sup>-1</sup> )				
C	45 A	39 B	40 b	44 a
N	5 A	4 B	4 a	5 a
Annual accumulation rates <sup>b</sup> (kg ha <sup>-1</sup> )				
C	500 A	200 B	200 b	500 a
N	78 A	6 B	27 b	57 a

<sup>a</sup> Means followed by the same upper case letters comparing carbon and nitrogen stocks in the soil within each cropping systems and the same lower case letters comparing grazing intensities are not significantly different by Tukey test at  $P < 0.05$ .

<sup>b</sup> The soil C and N accumulation rates were calculated as the difference between C stock in each treatment in relation to the treatment with lower stock (soybean/maize succession, grazing intensity moderate and stocking method continuous), divided by time of the experiment (14 years). Upper case letters compare means of cropping systems, and lower case letters compare means of grazing intensities by Tukey test  $P < 0.05$ .

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### Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.still.2020.104678>.

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