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Soil carbon indices as affected by 10 years of integrated crop–livestock production with different pasture grazing intensities in Southern Brazil

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ABSTRACT

Brazil has the world's second-largest cattle herd and second-largest no-till grain crop area. However, these activities are not frequently integrated because there is a widespread perception that cattle have a negative effect on cropping, especially when high crop yields are a goal. This misunderstanding of the synergy between pastures, livestock and crops is linked to overgrazing at the pasture rotation phase, which causes a decline in soil quality. Few studies have investigated the effect of pasture grazing intensities on soil carbon (C) balance and soil quality in subtropical environments. This work assessed the effects of different grazing intensities (0.10, 0.20, 0.30 and 0.40 m sward height) on soil C indices and animal productivity in a clay Haplorthox. The crop–livestock system model was a soybean/ryegrass plus black oat annual rotation managed for 10 years, using a randomized complete block design with three replications. Grazing intensity affected the quantity and composition of soil C input. Under heavy grazing with limited soil C input, there was a decrease in pasture and an increase in soybean participation in total C input. Soil organic C (0–0.20 m) under different grazing intensities had a linear relationship with C stratification ratio, C management index (CMI) and C pool index. Our results suggest that integrated crop–livestock systems could act as atmospheric C sources or sinks, depending on the grazing intensity. Pastures managed at 0.20 and 0.40 m height had the best balance between CMI and animal daily gain. The best balance between CMI and live weight gain per unit area occurred in sward height of 0.20 m.

1. Introduction

Total area of pastures in Brazil is approximately 172 million hectares (MAPA, 2013), of which 70% is currently estimated in some stage of pasture degradation. The majority of livestock production is carried out with free grazing and poor pasture management, making pasture degradation one of the biggest challenges of Brazilian livestock production, which reflects directly on the system's sustainability and ecosystem quality (Euclides et al., 2010). Among the main causes of pasture degradation are inadequate pasture management (Dubeux Jr. et al., 2007), high stocking rates and unbalanced nutrient replacement (Boddey et al., 2004). Consequently, weed infestation (Dubeux Jr. et al., 2007) and a progressive decline in soil quality (Marchão et al., 2009) was observed.

Total area of grain production in Brazil is approximately 52.2 million hectares (MAPA, 2013), with no-till systems representing approximately half of this area. One of the biggest challenges of no-till agriculture in tropical and subtropical environments is providing permanent soil cover and enough carbon (C) as crop residue input to account for climate conditions that promote fast crop residue decomposition and soil organic matter turnover (Amado et al., 2006; Bolinder et al., 2007; Sá et al., 2001).

The synergy between pasture, livestock and crops in an integrated crop–livestock system (ICLS) could meet these challenges

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Abbreviations: C, carbon; CMI, carbon management index; CPI, carbon pool index; CSR, carbon stratification ratio; DG, daily gain; ICLS, integrated crop–livestock system; POC, particulate organic carbon; RI, resilience index; SOC, soil organic carbon; WG, live weight gain per unit area.

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Table 1
Soil physical and chemical characterization in different sward heights in 2011.

Sward heights (m)	Physical attributes (0–0.10 m)	Chemical attributes (0–0.20 m)						
	Soil bulk density ($Mg\,m^{-3}$)	pH	P [a]	K [a]	Ca [a]	Mg [a]	CEC [b]	V [c]
		H_2O	$mg\,kg^{-1}$	$mmol_c\,kg^{-1}$			$cmol_c\,kg^{-1}$	%
0.10	1.32	4.28	13.02	2.10	39.20	23.40	11.67	55.61
0.20	1.23	4.30	11.60	2.10	41.00	24.20	10.25	65.78
0.30	1.30	4.12	9.94	1.90	34.20	20.70	9.58	59.41
0.40	1.23	4.20	16.91	2.70	39.20	24.10	14.25	46.30
GF	1.08	4.03	7.22	2.20	49.50	27.00	11.50	68.44

[a] Extracted with Mehlich-I.
[b] Cation exchange capacity.
[c] Base saturation.

of animal and grain production. In this system, the pasture phase could provide permanent soil cover and crop residue input required for a no-till system. Grain crops could improve overall soil fertility, because of the need for mineral fertilizer and lime inputs, and therefore increasing pasture vigor. Livestock, by producing dung and urine, could increase soil biological activity and nutrient recycling (Dubeux Jr. et al., 2009). Integrated crop–livestock system have proven to be effective in improving soil quality, breaking the cycle of pests and diseases, decreasing weed infestation, improving cash flow by diversifying income (i.e., by producing income from meat and grain) and providing sustainability to the production system (Franzluebbers, 2007; Sulc and Tracy, 2007).

Large-scale adoption of ICLS in Southern Brazil has been limited by the misconception that livestock during the pasture phase will have a negative effect on grain yields of the crop phase, particularly under no-till, because of minimal soil disturbance. Pasture overgrazing drives a progressive decline in soil quality because limited soil C input causes a lack of mulch that could otherwise prevent soil erosion (Franzluebbers, 2013), reduce soil compaction caused by agricultural machinery traffic (Reichert et al., 2009), stimulate biological activity, compensate for the fast residue decomposition in tropical environments and prevent weed infestation with species that are difficult to control chemically, such as horseweed (*Conyza bonariensis L. Cronquist*). According to Oldeman et al. (1991), approximately half of the world's agricultural land has severe soil degradation, notably in tropical and subtropical environments. Overgrazing is among the main causes of soil degradation.

Long-term studies are essential tools for understanding the effects of soil management on soil organic C (SOC) stocks changes (Bayer et al., 2009). There are few medium and long-term studies that investigate the relationship between pasture grazing intensities and SOC stocks under no-till in tropical climates.

Soil C indices are efficient early indicators of whether a given production system is driving the ecosystem to lose soil quality (Bayer et al., 2009), even before the SOC stocks has changed. According to Islam and Weil (2000), some fractions of SOC are important indicators of soil quality. The carbon management index (CMI) is an indicator of the quality of soil management and allows for a comparison of different systems with regard to their effects on soil quality (Diekow et al., 2005). Generally, high CMI values are associated with high soil quality in grain cropping systems (Bayer et al., 2009; Blair et al., 1995). Recently, this index was used as an indicator of the effects of pasture grazing intensity on soil quality (Carvalho et al., 2010; Souza et al., 2009).

Carbon stratification ratio (CSR) is the ratio between SOC from two different soil layers, usually the topsoil and an adjacent soil layer less affected by farming operations (Franzluebbers, 2002; Franzluebbers et al., 2007). Greater CSRs are related to soil management practices that enhance soil quality (Ferreira et al., 2013; Franzluebbers, 2002).

Research on soil C balance and soil quality in ICLS in tropical and subtropical climates is still scarce. This work assessed the effects of different grazing intensities (0.10, 0.20, 0.30 and 0.40 m sward height) on soil C indices and animal productivity in a clay Haplorthox. The study was conducted over a time span of 10 years using ICLS under no-till in subtropical Southern Brazil.

2. Materials and methods

2.1. Experimental field

The experiment was established in May of 2001 at the Espinilho farm, located in São Miguel das Missões, a county with a tradition of livestock production and recent expansion into grain crop production. The geomorphological unit corresponds to the Planalto Medio region in Rio Grande do Sul State (Southern Brazil; 28° 56′S and 54° 20′W, at an altitude of 425 m above the mean sea level). Soil is classified as Rhodic Haplorthox (Oxisol), deep, well drained, with a clayey surface texture of basaltic rock (540, 270 and 190 $g\,kg^{-1}$ of clay, silt and sand, respectively, in the 0–0.20 m soil layer). Soil physical and chemical characteristics are presented in Table 1. Climate is classified as Cfa (humid subtropical) according to the Köppen system of climate classification, with a mean annual rainfall of 1850 mm and an average temperature of 19 °C. Original vegetation was composed of gallery forest (GF) and natural pastures formed by grasses, predominantly *Paspalum notatum* Fluegge.

An integrated system of crops and livestock was adopted in 2001, with soybean (*Glycine max* (L.) Merrill) as the grain cash crop during summer and mixtures of black oat (*Avena strigosa* Schreb) and Italian ryegrass (*Lolium multiflorum* Lam.) grown during winter for grazing pasture. An experimental area of approximately 22 ha was divided into 12 plots ranging from 0.9 to 3.2 ha; four pasture grazing intensities were applied by managing pasture heights at 0.10, 0.20, 0.30 and 0.40 m, distributed in a randomized complete block design with three replications. The pasture heights were monitored every 15 days by the sward stick method (Barthram, 1986). Continuous put-and-take animal stocking was used to maintain desired pasture heights, as proposed by Mott and Lucas (1952).

Crossbred beef steers, approximately 10 months old and weighing approximately 199 kg, were used. The average stocking rates were approximately 6.7, 4.7, 3.1 and 1.7 steers ha^{-1} for pasture grazing heights of 0.10, 0.20, 0.30 and 0.40 m, respectively (Fig. 1). Grazing began in the first half of July and ended in the first half of November, with animal entrance occurring when the pasture reached an average dry matter accumulation of approximately 1,800 $kg\,ha^{-1}$. Animal daily gain (kg) was obtained by the difference between the initial and the final individual live weight of the tester animals during grazing duration. Live weight gain per unit area was obtained by multiplying the daily gain by the number of animals per hectare and per day. After 45 days from pasture seeding (May), urea top dressing of 45 $kg\,N\,ha^{-1}$ was applied. Detailed

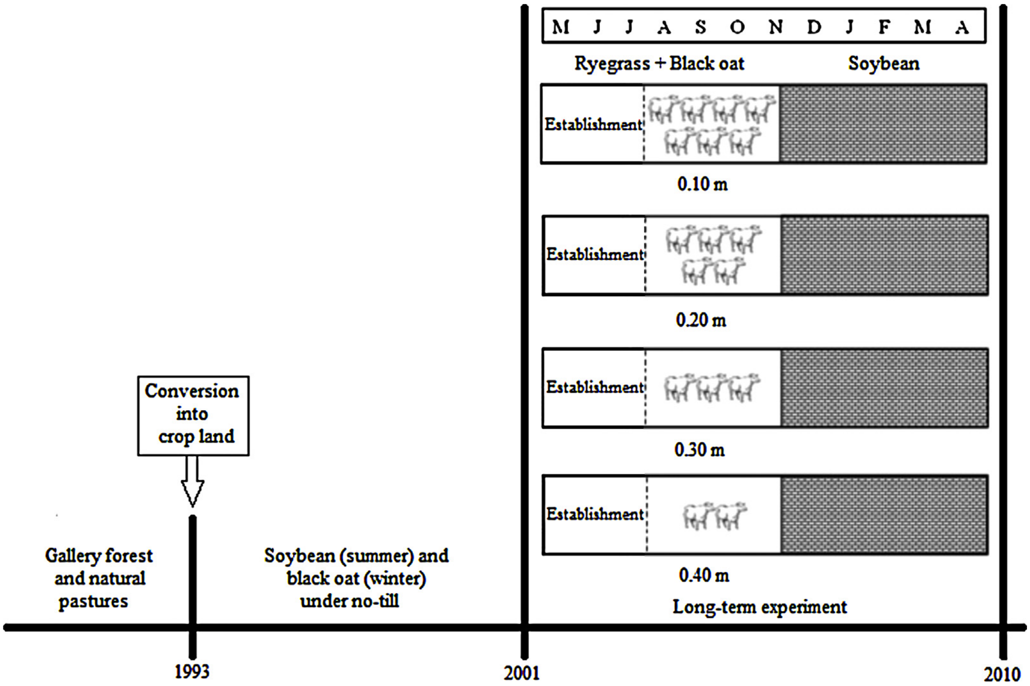

Fig. 1. Chronology of land use in the experimental area: before 1993 gallery forest and natural pastures; 1993, conversion of the original vegetation into crop land; 1993 to 2001, soybean in the summer and black oat in the winter were cultivated under conventional tillage; 2001 to 2010, installation of the integrated crop–livestock system with different grazing intensities. Average stocking rate was 6.7, 4.7, 3.1, and 1.7 steers ha^{-1} at 0.10, 0.20, 0.30, and 0.40 m sward height.

information regarding the temporal phases in the integration system and chronology of land is shown in Fig. 1.

After grazing, the pasture area was desiccated with glyphosate herbicide. Soybeans were established in November and harvested in April. The soybean cultivar was Nidera A6411 RR. Soybeans were sown at a density of 35 seeds m^{-2} with a row spacing of 0.45 m. Mineral fertilization rate was 240 kg ha^{-1} of 0-25-25 NPK, as recommended for a target yield of 4.0 Mg ha^{-1} and based on soil analysis data (CQFS RS/SC, 2004). To both phases (livestock and soybean yield), the gross income was evaluated considering the overall income obtained with sale of animals and soybean grains (Bremm et al., 2012).

Soil C input during the experimental period for each grazing intensity was based on research findings from Carvalho et al. (2011) that reported: (a) soybean yield, and (b) dry matter production of black oat plus ryegrass (Fig. 2). The root C input was estimated according to Sá et al. (2001). Plant C concentrations of 0.45 and 0.39 were used for black oat plus ryegrass (Sá, unpublished data) and soybean (Ferreira et al., 2012), respectively.

2.2. *Soil sampling, carbon stock and resilience index*

For this study, four soil composite samples from different grazing intensities treatments were collected in April of 2011 after the soybean harvest, at soil depths of 0–0.10 and 0.10–0.20 m. The soil samples from gallery forest was collected in May of 2010 at soil depth of 0–0.20 m. Soil bulk density was determined with steel rings having diameters of 0.085 m (EMBRAPA, 1997) at the same soil depths. Soil samples were air dried, freed of root and plant residue by manual manipulation, and later finely ground.

Soil physical fractionation analysis of the organic C was performed using the technique of Cambardella and Elliot (1992). Total organic C and particulate organic C (POC) were determined by dry combustion (Shimadzu VCSH), assuming that there were no carbonates as soil pH was ≤5.0. The SOC stocks were calculated based on equivalent soil masses (Ellert and Bettany, 1995), using the soil mass of an adjacent GF as the reference treatment.

Changes in SOC stocks (Mg ha^{-1} yr^{-1}) were estimated using Eqs. (1) and (2):

$$\text{Depletion rate} = \frac{(\text{SOC}_{\text{GF}} - \text{SOC}_{\text{Trt}})}{t} \qquad (1)$$

$$\text{Recovery rate} = \frac{(\text{SOC}_{\text{Trt}} - \text{SOC}_{\text{Trt10}})}{t} \qquad (2)$$

where SOC_{GF}, SOC_{Trt} and $\text{SOC}_{\text{Trt10}}$ refer to SOC stocks under GF, grazing intensity treatments, and treatment 0.10 m as “business as usual” (Carvalho et al., 2010), respectively; and *t* is the time in years since the conversion from GF and natural pastures into crop land and ICLS, totaling to 18 years.

Resilience index (*RI*) was evaluated as described by Dieckow et al. (2009) and Herrick and Wander (1997) to assess the rate of SOC recovery under different grazing intensities. In Eq. (3), the *RI* uses GF as the upper limit and Trt10 as the lower limit of SOC stocks:

$$RI = \frac{(\text{SOC}_{\text{Trt}} - \text{SOC}_{\text{Trt10}})}{(\text{SOC}_{\text{GF}} - \text{SOC}_{\text{Trt10}})} \qquad (3)$$

2.3. *Carbon stratification ratio, carbon pool index and carbon management index*

The CSR was calculated as proposed previously by Franzluebbers (2002):

$$\text{CSR} = \frac{(\text{SOC in topsoil layer } (0-0.10\ \ \text{m}))}{(\text{SOC in adjacent soil layer } (0.10-0.20\ \ \text{m}))} \qquad (4)$$

Soil depths used in this study were selected based on Causarano et al. (2008), who reported that these soil depths were appropriate for investigating relationships between CSR and SOC stocks and between CSR and soil quality.

Table 2
Harvest and root dry matter indices and percentage of carbon in the crop residue [a].

Cropping systems	Harvest index [‡]	Root dry matter index [‡]	Carbon in the crop residue ($g\,kg^{-1}$) [‡‡]
Soybean	0.89 (±0.02)	0.20 (±0.01)	39.5 (±0.02)
Italian ryegrass + black oat	1.00 (±0.01)	0.23 (±0.02)	45.0 (±0.03)

[a] As proposed by Sá et al. (2001).

[‡] Index values of 0.89 and 0.20 for soybean cultivation indicate that 1 Mg of grain yields the equivalent of 0.89 Mg of dry matter for aerial parts and 0.20 Mg for soybean roots.

[‡‡] Determined by dry combustion.

The carbon pool index (CPI) was calculated as described by Blair et al. (1995), as follows:

$$\mathrm{CPI} = \frac{(\mathrm{SOC_{trt}}\ \text{in soil layer}\ (0-0.20\quad \mathrm{m}))}{(\mathrm{SOC_{ref}}\ \text{in soil layer}\ (0-0.20\quad \mathrm{m}))} \tag{5}$$

where $\mathrm{SOC_{trt}}$ = soil organic carbon in given grazing intensity treatment and $\mathrm{SOC_{ref}}$ = soil organic carbon in the reference treatment (GF).

The CMI was obtained as described by Blair et al. (1995) with the adaption of Vieira et al. (2007):

$$\mathrm{CMI} = CPI \times LI \times 100 \tag{6}$$

where *LI* is the lability index.

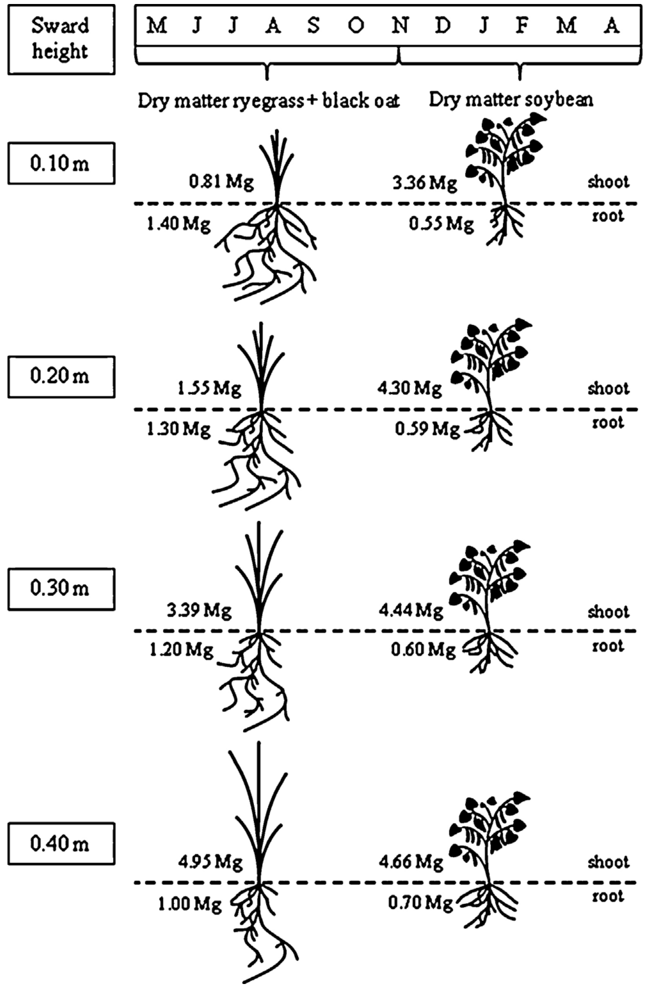

Fig. 2. Relationship between residual dry matter (shoot and root; $\mathrm{Mg\,ha^{-1}\,yr^{-1}}$) in the different grazing intensities. Data from Carvalho et al. (2011).

The *LI* is calculated as follows:

$$LI = \frac{(L\ in\ treatment)}{(L\ in\ reference)} \tag{7}$$

where *L* refers to the C lability, calculated as:

$$L = (labile\ C)/(non\text{-}labile\ C) \tag{8}$$

In this study, POC was defined as the labile pool, and the mineral-associated organic carbon (MAOC) was defined as the non-labile pool. The GF was considered as the reference (CMI = 100).

2.4. *Soil C balance*

Soil C balance was calculated using the unicompartmental model proposed by Henin and Dupuis (1945). The model estimates C balance based on the dynamic equilibrium concept ($dC/dt = 0$) of SOC requiring the quantity of C input by plant biomass and C losses through biological oxidation according to Eq. (9):

$$\frac{dC}{dt} = -K_2C + K_1A \tag{9}$$

where dC/dt = annual rate of SOC variation in $\mathrm{Mg\,ha^{-1}}$, A = quantity of C input by crop residues annually in $\mathrm{Mg\,ha^{-1}}$, K_1 = the humification coefficient represented by the percentage of C input that will build up SOC, C = the SOC stock in $\mathrm{Mg\,ha^{-1}}$, and K_2 = the annual coefficient of SOC lost by biological oxidation.

The following indices were used as additional parameters in the soil *C* balance:

Harvest index: Quantity of grain harvested as a fraction of total plant dry matter of the crop (Table 2).

Root dry matter index: Quantity of root dry matter produced as a fraction of total biomass (Table 2).

K_1: Humification coefficient was assumed based on Campos (2006); $K_1 = 0.194$ for a grain crop rotation system in the same region as our study.

K_2: oxidation coefficient for SOC. $\mathrm{K_2} = 0.012$ was used as previously proposed by Bayer (1996) from the same region as the present study.

Data on grain yields, shoot, root and total dry matter obtained for the crops in ICLS are summarized in Table 2.

2.5. *Statistical analysis*

Results were subjected to an analysis of variance using the software SISVAR 5.0 (Ferreira, 2010). Means were compared using the Tukey test ($p < 0.05$). Regression analysis was performed using JMP IN version 7.0.1 (Sall et al., 2005).

3. Results and discussion

3.1. *Dry matter pasture and crop residue input (shoot and root) in different grazing intensities*

The effects of pasture grazing intensity on biomass input to soil are shown in Fig. 2. The average amount of total dry matter

Table 3
Average carbon input derived from the dry matter (shoot + root) of winter and summer crops in the different grazing intensities under integrated crop–livestock system.

Cropping systems	Grazing intensities	C input
	(m)	Mg ha^{-1} yr^{-1}
Italian ryegrass + black oat (W[*])	0.10[§]	0.99 c (±0.08)
	0.20	1.28 c (±0.26)
	0.30	2.07 b (±0.09)
	0.40	2.68 a (±0.27)
Soybean (S[**])	0.10	1.55 b (±0.26)
	0.20	1.93 ab (±0.20)
	0.30	1.99 ab (±0.06)
	0.40	2.12 a (±0.21)

[*] Winter.

[**] Summer.

[§] Sward height (m).

Averages followed by the same letters, in the columns, do not differ by the Tukey test, to the level 5% of significance. Comparison is between grazing intensities (in the same cropping systems).

Table 4
Soil organic carbon (SOC), particulate organic carbon (POC) and mineral-associated organic carbon (MAOC) stocks (Mg ha^{-1}) in 0–0.20 m soil layer for different grazing intensities under integrated crop–livestock system in Oxisol from South Brazil.

Grazing intensities (m)	SOC	POC (Labile C)	MAOC (Non-labile C)
	Mg ha^{-1}		
Gallery forest	59.07 a (±2.19)	8.97 a (±1.54)	50.10 a (±2.20)
0.10[§]	44.08 b (±0.19)	3.72 c (±0.77)	40.79 b (±2.75)
0.20	46.60 b (±0.15)	4.45 bc (±0.76)	42.16 b (±1.64)
0.30	45.00 b (±1.26)	4.02 bc (±0.23)	41.28 b (±0.60)
0.40	46.51 b (±1.32)	4.89 b (±0.45)	41.53 b (±1.12)

Means followed by the same letter, in the columns, do not differ by the Tukey's test ($p < 0.05$).

[§] Sward height (m).

input (shoot + root) to soil from black oat plus ryegrass, ranged from 2.21 to 5.95 Mg ha^{-1} yr^{-1} for heavy grazing intensity (0.10 m sward height) and low grazing intensity (0.40 m sward height), respectively; at the total dry matter input from soybean, ranged from 3.91 to 5.36 Mg ha^{-1} yr^{-1} for heavy grazing intensity and low grazing intensity, respectively. Pasture management affected plant partitioning between shoot and root. Increasing the height of the sward increased residual dry matter of the shoot input; however, root mass decreased. Under low sward height, residual dry matter of the shoot decreased, but this change was accompanied by an increase in root mass input. This plant behavior was observed previously by Conte et al. (2007) and is a physiological plant response to grazing stress (Chen et al., 2006). Pasture management with heavy grazing intensity stimulates plant tillering and, as a consequence, growth of new roots (Hodgson, 1990). Pasture management with lower grazing intensity stimulates constant shoot renewal and therefore reduces root growth (Carvalho et al., 2011).

The treatment 0.40 m sward height had 16% more input from aboveground biomass of black oat plus ryegrass in relation to treatment 0.10 m sward height. The results suggest that greater residual pasture shoot dry matter is favorable to soybean growth. Permanent soil cover is a prerequisite for the success of no-till systems (Derpsch et al., 2010). Increasing pasture residual dry mass input results in greater soil cover, there by increasing water infiltration, reducing soil temperature and evaporation and stimulating soil biological activity (Amado et al., 2006). Under conditions of covered soil, greater soil moisture has been frequently reported, stimulating plant growth (Fageria et al., 2011). Weed infestation had a negative linear relationship with the quantity of residue input (Dubeux Jr. et al., 2007). Therefore, greater residual pasture input plays an important role as a weed control strategy in the soybean phase. Soybean nodulation is stimulated by maintaining soil cover (Ferreira et al., 2000) and results in greater aboveground biomass production.

Table 3 shows the average amount of C input to soil from plant residues under different grazing intensities. Concerning the black oat plus ryegrass, the soil C input ranged from 0.99 to 2.68 Mg C ha^{-1} yr^{-1}. Concerning the soybean, the input ranged from 1.55 to 2.12 Mg C ha^{-1} yr^{-1} (Table 3). In addition to affecting total C input (which ranged from 2.54 to 4.80 Mg ha^{-1} yr^{-1} for heavy and low grazing intensity, respectively) there was an effect on composition of C input. Black oat plus ryegrass participation in total C input was 39, 40, 51 and 56% for 0.10, 0.20, 0.30 and 0.40 m sward height treatments, respectively. A decrease in pasture participation in soil C input has consequences for the quality of no-till systems. Soybean crop residues have a low C/N ratio and therefore decompose quickly, remaining on the soil surface for only a short time. On the other hand, the mixture of black oat plus ryegrass with a high C/N ratio results in longer soil protection (Mauli et al., 2011). Balbinot Junior et al., 2004 concluded that a mixture of forages produces greater biomass than single species. Mauli et al. (2011) suggests that this diversity leads to better use of natural resources, decreased pest problems and enhanced nutrient cycling.

3.2. *SOC stocks affected by different grazing intensities*

The SOC stocks ranged from 44.1 to 46.5 Mg ha^{-1} for heavy and lower grazing intensities. Conversion of GF and natural pastures into crop land and adoption of 10 years of an ICLS resulted in an average decline of approximately 23% in SOC stocks, representing an emission of 49.5 Mg CO$_2$ ha^{-1} (Table 4). Considering that land use change occurred during the 1960s and assuming that no SOC was lost after the ICLS establishment, annual SOC lost was 0.34 Mg ha^{-1} yr^{-1}. Davidson and Ackerman (1993) estimated that the conversion of native forest to crop land resulted in a decrease of 20 to 30% of the original SOC stocks. Van Den Bygaart et al. (2003) reported a decrease of 24% in SOC stocks when native forest was replaced by crop land in Canada. In Rio Grande do Sul, Tornquist et al. (2009) reported a severe SOC decline of 44–50% in agriculture systems.

Stocks of SOC were statistically similar among pasture management systems (Table 4). The medium term experiment may not have provided enough time for treatments to express their effects on SOC stocks. Although not significant, the decrease in SOC stocks relative to GF for the 0–0.20 m soil depth was 15.0, 12.5, 14.1 and 12.6 Mg ha^{-1} for sward height of 0.10, 0.20, 0.30 and 0.40 m, respectively. Greatest loss of SOC (25%) was observed in the heavy grazing intensity treatment. This treatment had low carbon input derived from the dry matter (shoot + root) of the winter crop contribution (0.99 Mg C ha^{-1} yr^{-1}) resulting in less total biomass carbon input (2.54 Mg C ha^{-1} yr^{-1}) (Table 3). The C balance of soybean was expected to be negative or neutral according to studies carried out with eddy covariance (Hollinger et al., 2005). Under heavy grazing intensity, loss of SOC was explained by greater removal of photosynthetic plant tissue and subsequent respiration of assimilated C by grazers, reducing C inputs to build up SOC (Klumpp et al., 2009). Low and moderate (0.20 m sward height) grazing intensity treatments had lower SOC losses and were associated with higher C input than high grazing intensity (Table 3). Previously, Marchão et al. (2009) reported SOC depletion in ICLS (52.2 Mg ha^{-1}) compared to native vegetation (60.9 Mg ha^{-1}). However, the SOC decline was less in magnitude.

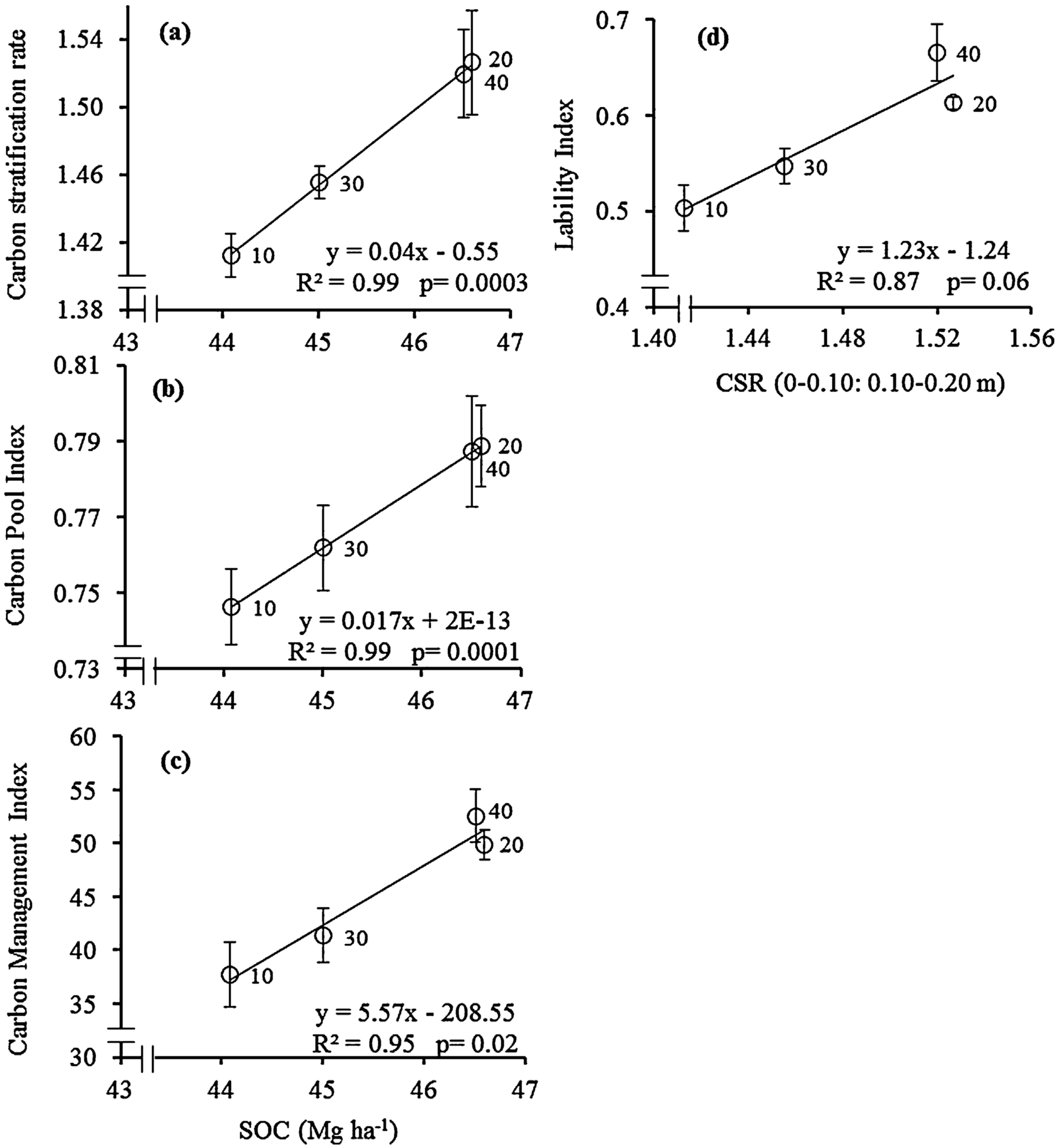

Fig. 3. Relationship between SOC stocks in the 0–0.20 m soil depth and carbon stratification ratio (CSR) (0–0.10: 0.10–0.20 m) (a), carbon pool index (CPI) (b) and carbon management index (CMI) (c). Relationship between CSR and lability index (*LI*) (d). Grazing intensity= 0.10, 0.20, 0.30 and 0.40 m sward height.

Table 5
Carbon stratification ratio (CSR), carbon pool index (CPI), carbon management index (CMI) and lability index (LI) indices (Mg ha^{-1}) in 0–0.20 m soil layer for different grazing intensities under integrated crop–livestock system in Oxisol from South Brazil.

Grazing intensities (m)	CSR	CPI	CMI	*LI*
	(0–0.10: 0.10–0.20 m)			
0.10[§]	1.41 b (±0.01)	0.75 a (±0.01)	37.80 b (±3.0)	0.50 b (±0.02)
0.20	1.53 a (±0.03)	0.79 a (±0.01)	49.80 ab (±1.4)	0.61 ab (±0.01)
0.30	1.46 ab (±0.01)	0.76 a (±0.01)	41.40 ab (±2.5)	0.55 ab (±0.02)
0.40	1.52 a (±0.03)	0.79 a (±0.01)	52.60 a (±2.48)	0.67 a (±0.03)

Means followed by the same letter, in the columns, do not differ by the Tukey's test ($p < 0.05$).

[§] Sward height (m).

Table 6
Soil carbon balance in different pasture management investigated by the carbon model proposed by Henin and Dupuis (1945) using the 0–0.20 m soil depth as reference.

Grazing intensities (m)	Biomass added [†]			C input	$K_1 \times A$ [§]	C	$K_2 \times C$[‡‡]	C balance
	AP [††]	Root	Total		(Annual)	Stock [§§]	(Annual)	dC/dt [§§§]
	Mg ha^{-1}							
0.10[*]	4.17 d (±0.54)	1.95 a (±0.02)	6.12 d (±0.50)	2.54 d (±0.21)	0.50 d (±0.04)	44.08 a (±0.19)	0.53 a (±0.05)	−0.04 d (±0.03)
0.20	5.85 c (±0.91)	1.89 ab (±0.09)	7.74 c (±1.00)	3.21 c (±0.39)	0.63 c (±0.06)	46.60 a (±0.15)	0.56 a (±0.04)	0.06 c (±0.03)
0.30	7.83 b (±0.25)	1.80 b (±0.03)	9.63 b (±0.30)	4.06 b (±0.11)	0.79 b (±0.02)	45.00 a (±1.26)	0.54 a (±0.02)	0.25 b (±0.05)
0.40	9.61 a (±0.60)	1.70 c (±0.01)	11.30 a (±0.60)	4.80 a (±0.26)	0.93 a (±0.05)	46.51 a (±1.32)	0.56 a (±0.02)	0.37 a (±0.07)

Means followed by the same letter, in the columns, do not differ by the Tukey's test ($p < 0.05$).

[†] Biomass added over one year: Italian ryegrass intercropped with black oat + soybean.

[††] AP = aerial part.

[§] $K_1 \times A$ = humidified carbon based on the coefficient ($K_1 = 0.194$) proposed by Campos (2006), where, A = carbon input.

[§§] C stock.

[‡‡] $K_2 \times C = C$ loss calculated based on the oxidation coefficient, $K_2 = 0.012$ proposed by Bayer (1996), where, $C = C$ stock.

[§§§] $dC/dt = -K_2C$[‡‡] $+ K_1A$[§].

[*] Sward height (m).

3.3. *Relationships of SOC, CSR, CPI, CMI and LI*

The SOC stocks (0–0.20 m) had a linear relationship with CSR ($p < 0.0003$) in the ICLS treatments (Fig. 3a). In our study, the CSR ranged from 1.41 (±0.01) to 1.53 (±0.03) under heavy and low grazing intensities, respectively (Table 5). Salton (2009) reported CSR values for an ICLS ranging from 1.40 to 1.64 in a tropical environment with a clayey Oxisol. Ferreira et al. (2013) reported similar CSR values (1.39 to 1.72) for Oxisols from Rio Grande do Sul State (Brazil) managed under no-till grain systems. In Paraná State (Brazil), Tormena et al. (2004) reported a CSR of 1.73 in a Red Distroferric Oxisol managed under no-till.

The strong relationship between SOC and CSR is the result of continuous aboveground C input and minimal soil disturbance to establish pasture and cash crops. Franzluebbers (2013) reported that a high CSR helps to reduce soil erosion and runoff and stimulates soil biological activity and diversity, improving soil quality and the environment. The CSR had a linear relationship with the LI, suggesting that the quality of SOC is improved by surface crop residue input (Fig. 3d).

Pasture heights of 0.20 and 0.40 m were considered to have high soil quality based on CSR values of 1.53 (±0.03) and 1.52 (±0.03), respectively (Table 5). Sward height of 0.10 m was classified as having low soil quality, with a CSR value of 1.41 (±0.01). Franzluebbers (2002) suggested a CSR of 2.0 as a critical limit for maintaining soil quality in temperate climates. In our study, CSR values were lower than this limit (Table 5) due to the higher oxidative conditions in tropical and subtropical climates which explained the lower CSR (Ferreira et al., 2013). There is a need to establish critical CSR values for ICLS in tropical and subtropical climates.

The CPI has been reported as an efficient indicator of soil quality in temperate (Blair et al., 1995) and subtropical soils (Bayer et al., 2009). In our study, SOC stock (0–0.20 m) had a linear relationship with CPI ($p < 0.0001$) (Fig. 3b). The CPI ranged from 0.75 (±0.01) to 0.79 (±0.01) under heavy and low grazing intensities, respectively (Table 5). These CPI were lower than those reported in other works (Carvalho et al., 2010; Souza et al., 2009) on the same site, because the reference treatment was ungrazed natural vegetation.

The SOC stocks (0–0.20 m) also had a linear relationship with CMI ($p < 0.02$) (Fig. 3c). The CMI ranged from 37.80 (±3.00) to 52.60 (±2.48) under heavy and low grazing intensities, respectively (Table 5). The heavy grazing intensity indicated a loss of SOC quality (CMI), being approximately 28, 24 and 9% less compared to treatment 0.40, 0.20 and 0.30 m, respectively. These results are in agreement with those presented by Souza et al. (2009), where the highest CMI was reported under moderate grazing intensity (0.20 m sward height) in comparison to treatments without grazing. Conte et al. (2011) and Salton (2009) reported similar results.

All C indices consistently ranked treatments and were useful indicators of changes in soil quality induced by grazing intensity (Fig. 3).

3.4. *Carbon balance in integrated crop–livestock system*

The C balance affected by different grazing intensities is shown in Table 6. The C balance ranged from −0.04 (±0.03) to 0.37 (±0.07) Mg ha^{-1} yr^{-1} under heavy and low grazing intensities, respectively. The heavy grazing intensity acted as source of C to the atmosphere, while the moderate grazing intensity treatment was a slight sink. The treatments with 0.30 and 0.40 m sward heights acted as an atmospheric C sink in the range of 0.25 (±0.05) to 0.37 (±0.07) Mg ha^{-1} yr^{-1}, respectively. These results were in agreement with Santos et al. (2011), who reported a C sequestration rate of 0.32 Mg ha^{-1} yr^{-1} over a two-year ryegrass pasture/grain crop rotation. Conant et al. (2001) reported a C sequestration rate ranging from 0.11 to 3.04 Mg ha^{-1} yr^{-1}, with an average of 0.54 Mg ha^{-1} yr^{-1}.

These results suggest increased pasture grazing compromises the potential of an ICLS to act as a C sink. This result is attributed to the decrease of pasture in the composition of total C input under heavy grazing intensity (Table 3) and with soybean monocropping, consequently reflecting a lower quality of soil (Fig. 3). Mcsherry and Ritchie, 2013 showed that pasture using C4 plants drives soil C retention in comparison to soybean, a C3 plant. Studies carried out in the USA showed that soybeans contribute 0.15 Mg ha^{-1} yr^{-1} to the atmosphere (Hollinger et al., 2005). These results were attributed to a limited root system (Fig. 2), a low C/N ratio, and a high amount of C removed by harvest. Therefore, under soybean monocropping, the ICLS could act as C sink only if the residual pasture C input was enough to compensate for the C loss in the crop phase. Souza et al. (2009) reported that C loss in an ICLS could be associated with pasture degradation (loss of plant vigor), high C residue removed by grazing and high soil respiration from an increase in biological activity due to excrement input from livestock. From an environmental point of view, the ICLS acted as an atmospheric C sink when the pasture grazing intensity was light (0.30 and 0.40 m sward height) (Table 6).

Ferreira et al. (2012), investigating the C balance in a clay Oxisol managed under no-till, reported a demand for 6.5 Mg ha^{-1} yr^{-1} of dry matter input to achieve soil C equilibrium. In our study, C input of >4.0 Mg ha^{-1} yr^{-1} with pasture participation of >50% of total C input was necessary for ICLS to act as a C sink (Table 6).

Table 7
Depletion rate, recovery rate and resilience index after conversion gallery forest and natural pastures into crop land and conversion from crop land to integrated crop–livestock system in South Brazil.

Grazing intensities (m)	Depletion rate [§]	Recovery rate [§§]	RI [§§§]
0.10[*]	0.83 a (±0.02)	–	–
0.20	0.69 b (±0.04)	0.14 a (±0.02)	0.17 a (±0.04)
0.30	0.78 a (±0.02)	0.05 b (±0.03)	0.06 b (±0.02)
0.40	0.70 b (±0.02)	0.14 a (±0.02)	0.16 a (±0.02)

Means followed by the same letter, in the columns, do not differ by the Tukey's test ($p < 0.05$).

[§] Depletion rate = $(\mathrm{SOC_{GF}} - \mathrm{SOC_{trt}})/t$.

[§§] Recovery rate = $(\mathrm{SOC_{trt}} - \mathrm{SOC_{trt10}})/t$.

[§§§] $RI = (\mathrm{SOC_{trt}} - \mathrm{SOC_{trt10}})/(\mathrm{SOC_{GF}} - \mathrm{SOC_{trt10}})$.

[*] Sward height (m).

3.5. Resilience index

Assuming that soil resilience is the capacity of soil to recover its functional and structural integrity after a disturbance or stress, and using a heavy grazing intensity as the disturbance treatment, we calculated RI for different grazing intensities, based on the conceptual approach of Herrick and Wander (1997). The moderate and low grazing intensities showed the highest RI (Table 7). The 0.30 m sward height treatment showed an intermediate RI value, which was most likely due to lower root C input compared with the 0.20 m sward height and lower shoot C input compared to the 0.40 m sward height (Fig. 2). Santos et al. (2011) showed that root C input plays a crucial role in soil C accumulation.

3.6. Livestock and crop productivity relationships with soil quality

Integrated systems of livestock and grain crop production should be designed to stimulate the synergistic interactions between animals, plants and soils, using a holistic approach in which the integrity and functionality of the whole system is more important than one specific phase. For example, if cattle are not removed from winter pasture early enough, overgrazing with negative consequences to the next phases of the ICLS could occur. Integrated systems will only achieve high levels of efficiency when all phases are working in harmony.

Heavy grazing intensities are generally associated with short-term degradation of pasture (Almeida et al., 2000) and with medium and long-term unsustainability of the whole integrated system. Mott (1973) reported that optimal grazing intensity should reconcile the gain per area and the gain per animal without exploiting the pasture and soil quality.

In Fig. 4, relationships of animal productivity, grazing intensities and CMI, as an indicator of soil quality, are shown. Animal performance per area is inversely related to sward height. Thus, highest animal gain (Fig. 4a) and gross income (Fig. 4c) were observed in the 0.10 m sward height, but soil quality (CMI) was lowest. These results suggest that the positive gross income in this treatment would be unsustainable in the long-term because it was at the expense of soil quality (Table 6). Other side effects reported from the heavy grazing intensity were degradation of physical and biological soil attributes (Flores et al., 2007). Limited plant residue input to soil (Table 6) is unfavorable for the sustainability of a no-till system (Carvalho et al., 2010; Ferreira et al., 2012).

The 0.40 m sward height yielded the smallest animal gain per unit area (Fig. 4a) and lowest gross income (Fig. 4c) but showed the highest CMI, suggesting that its main effect was to enhance soil quality and environmental protection (Table 4).The treatment that provided a balance between soil quality, animal performance and economic return was the 0.20 m sward height. This treatment had higher animal gain per unit area without compromising soil quality (Fig. 4) and pasture persistence (Carvalho et al., 2011).

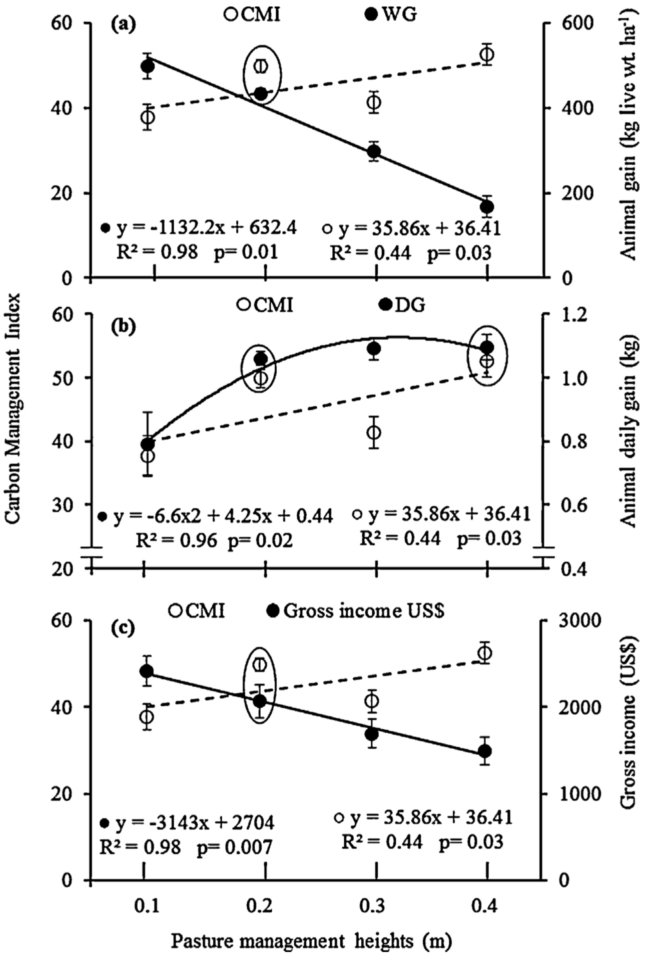

Fig. 4. Relationship between different grazing intensities and carbon management index (CMI), and live weight gain per unit area (WG) (a); CMI and animal daily gain (DG) (b) and CMI and gross income (US$) (c). WG and DG = averaged of 2001–2010. Source: Carvalho et al. (2011) and Bremm et al. (2012).

The 0.10 m sward height had poor animal daily gain (Fig. 4b), delayed termination of steers at the end of the grazing cycle, and had poor soil quality (Fig. 4b), suggesting an unsustainable system (Almeida et al., 2000). The best balance between soil quality and animal daily gain occurred in sward heights of 0.20 and 0.40 m. The daily gain value under moderate grazing intensity was 95% of maximum (1.12 kg) at 0.32 m sward height (based on the equation $y = 0.44 + 4.25X - 6.6X^2$, Fig. 4b). Therefore, moderate grazing intensity allows early termination of steers during the pasture cycle, an attractive gross income, and maintains or enhances soil quality.

4. Conclusions

The SOC stocks under different grazing intensities was related to indices of soil quality. The highest CSR and CPI were found in the treatment with moderate grazing intensity.

The integrated crop–livestock system acts as source or a sink of atmospheric carbon depending on the grazing intensity. Under heavy grazing intensity, the system was a source (0.04 Mg ha^{-1} yr^{-1}), and under light grazing intensity, it was a sink in the range of 0.25 to 0.37 Mg ha^{-1} yr^{-1}.

Pastures managed at 0.20 and 0.40 m sward height had the best balance between CMI and animal daily gain. The best balance between CMI and live weight gain per unit area, CMI and economic return, occurred in sward height of 0.20 m.

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