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Mitigation of enteric methane emissions through pasture management in integrated crop-livestock systems: Trade-offs between animal performance and environmental impacts

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ABSTRACT

We evaluated the effect of different grazing intensities by steers on animal performance, herbage intake and CH_4 emissions in the stocking period of a soybean-beef cattle integrated system in southern Brazil. Treatments consisted of different grazing intensities, defined by target sward heights (10, 20, 30 and 40 cm) of mixed black-oat (*Avena strigosa* Schreb.) and Italian ryegrass (*Lolium multiflorum* Lam.) pastures under continuous stocking. Grazing management affected herbage utilization and, consequently, animal performance and CH_4 emission. At the individual level, CH_4 emission and animal performance had optimal values when pasture height was managed within a range of 23–30 cm. At the farm level, we found a positive linear effect of grazing intensity on animal live weight gain per hectare and the associated environmental costs of land use. Liveweight gain increased by 90 g ha^{-1} day^{-1} and CH_4 emissions increased by 500 g CO_2eq ha^{-1} day^{-1} for each cm of target sward height reduction. Given that most producers graze pastures to very short heights, large-scale adoption of target heights within 23–30 cm in southern Brazil has the potential to achieve 13–14% of the mitigation target for GHG emissions from the whole agricultural sector and 22–25% of the target for enteric fermentation from the livestock sector pledged by the Brazilian Government in the Paris Agreement. We conclude that adequate grazing management is the key strategy to improve animal production and reduce the environmental impact from livestock in ICLS.

1. Introduction

Climatic changes due to anthropogenic greenhouse gas (GHG) emissions are a crucial threat to future food production (IPCC, 2014), requiring a strict reduction in this environmental footprint. However, world population is still growing and projections surpass 9.7 billion people by 2050 (UN, 2017). As a result, meat demand will increase by over 200 percent in low- and middle-income countries in the same time frame (FAO, 2018).

Ruminants are implicated as major contributors to GHG emissions in agriculture (Gerber et al., 2013) with enteric fermentation and manure accounting for 36–48% (or 2.0–3.6 Pg CO_2eq yr^{-1}) of total GHG emissions in the livestock sector (Herrero et al., 2016). Methane (CH_4) alone accounts for up to 43% of total emissions, while the remaining part is equally shared between nitrous oxide and carbon dioxide from manure management, feed production and other farm and post-farm operations (Herrero et al., 2016). The utilization of appropriate management practices in pasture-based livestock systems constitutes an important mitigation option, as about twenty billion animals make use of 30% of the world's lands for grazing (Steinfeld et al., 2006).

Mitigation of ruminant CH_4 emissions is particularly important in Brazil, which is the second largest beef producer in the world (USDA, 2018). However, more than half is produced on degraded

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pastures (de Oliveira Silva et al., 2017), representing a considerable mitigation opportunity. Improved grazing management has the potential to mitigate GHG emissions through reducing CH_4 emission intensities (i.e., CH_4 emissions per kg of animal product) due to higher individual performances from pasture improvements or adjusted stocking rates (Thornton and Herrero, 2010; Savian et al., 2018) and through carbon sequestration in soil (Franzluebbers and Stuedemann, 2009). Adjusting grazing intensity to allow greater forage production has the potential to annually sequestrate 150 Tg CO_2eq yr^{-1} in the world grazing lands' soils, while other management practices such as legume sowing or fertilization could raise carbon sequestration to even higher levels (Henderson et al., 2015).

Adequate grazing management could be even more promising if applied in the stocking period of an integrated crop-livestock system (ICLS), since crop-livestock integration has been considered an effective way to approach the sustainable intensification of agricultural systems (FAO, 2010). It is estimated that about 11.5 million ha^{-1} in Brazil, or 5.5% of cultivated area, are currently under ICLS, a 600% growth compared to 2005. Rio Grande do Sul state in southern Brazil has the highest ICLS adoption rate at 21% of cultivated land (Embrapa, 2016). However, despite the potential benefits of crop-livestock integration to agroecosystems' efficiency and resilience (Lemaire et al., 2014; Peterson et al., 2018), little is known about GHG mitigation opportunities in ICLS, especially CH_4 emissions from cattle.

Many studies regarding GHG mitigation have investigated the effect of feed additives (McGinn et al., 2004; Grainger and Beauchemin, 2011) or crop-derived concentrates (Martin et al., 2008; Beauchemin et al., 2009) on CH_4 emissions, but these alternatives imply costs and the utilization of human-edible food for animal feeding. Another alternative of growing research interest is the utilization of plant extracts and secondary compounds as feed additives, but these have not yet shown evidence of mitigation potential and require further research (Martin et al., 2008). A summary of supply-side mitigation options is listed in IPCC Fifth Assessment Report, and many studies relate adjusted stocking rates to carbon sequestration and N_2O emissions in grazing lands, but there is no literature addressing the effect of this strategy on ruminant CH_4 mitigation, even though it is considered an easy to implement and universally applicable strategy (IPCC, 2014).

Therefore, this study aimed to test the hypothesis that adequate grazing management that allows for a supply of sward structures that maximize plant and animal productivity in the inter-crop period of an ICLS have the potential to mitigate ruminant CH_4 emissions, decreasing the environmental footprint associated with pasture-based livestock systems. For this purpose, we evaluated the effect of different grazing intensities by steers on animal performance, herbage intake and CH_4 emissions in the stocking period of a soybean-beef cattle integrated system in southern Brazil. We believe our work is the first to use grazing management as the only tool to address CH_4 mitigation in ICLS, as well as the potential tradeoffs related to grazing intensification.

2. Material and methods

2.1. Site description and experimental design

The study site is located at Espinilho Farm, in São Miguel das Missões district (28°56′14.00″ S, 54°20′45.61″ W; 465 m ASL), in the main grain-producing region of the Rio Grande do Sul State, southern Brazil (IBGE, 2017). The region has a warm, humid subtropical climate (Cfa in the Köppen classification system), with an average annual temperature of 19 °C and average annual precipitation of 1850 mm. The soil is a clayey Rhodic Hapludox (Soil Survey Staff, 1999). Since 2001, soybean [*Glycine* max (L.) Merr.] was grown in the summer and a mixture of black-oat (*Avena strigosa* Schreb.) and Italian ryegrass (*Lolium multiflorum* Lam.) pastures in the winter, in a soybean-beef cattle integrated system focusing on fattening and slaughter of the grazing animals.

The experimental design was a randomized complete block with three replicates. Paddocks were subjected to four treatments (grazing intensities), defined by target sward heights under continuous stocking: intense grazing, 10 cm (G10); moderate grazing, 20 cm (G20); moderate-light grazing, 30 cm (G30); and light grazing, 40 cm (G40); resulting in 12 grazed paddocks varying from 0.9 to 3.6 ha. The variable stocking rate method (Mott and Lucas, 1952) was used to maintain target sward heights in the grazed paddocks. Three tester animals per paddock remained throughout the entire stocking period with a variable number of 'put-and-take' animals, with the adjustments performed every 15 days. Individual performance and CH_4 emission evaluations were done only in the tester animals.

Field evaluations were carried out from April to November in two stocking periods (2013 and 2014). Pasture establishment occurred after soybeans were harvested in April, with black-oat cv. IAPAR 61 sowed in rows at a rate of 60 kg ha^{-1}. Italian ryegrass was established by natural reseeding and supplemented by sowing (30 kg ha^{-1} seeding rate). Nitrogen fertilization was applied as urea (140 kg N ha^{-1}) in two equally partitioned applications 30 and 45 days after sowing. In the first year (2013), stocking period began with the entrance of animals into the experimental area on June 24th, when pasture reached an average sward height of 29 ± 2.7 cm and herbage mass of 1858 ± 218.0 kg dry matter (kg DM ha^{-1}).

2.2. Sward measurements

Sward height (SH, cm) was monitored every 15 days with a sward stick (Barthram, 1984), randomly measuring 100 points per paddock. Herbage mass (HM, kg DM ha^{-1}) assessments were performed monthly using the double sampling technique (Wilm et al., 1944). Five cuts were performed at ground level in 0.25 m^2 randomly located quadrats in each experimental unit. Daily herbage accumulation rate (DHA, kg DM ha^{-1}) was monitored using three grazing exclusion cages per paddock (Klingman et al., 1943), according to the methodology described by Kunrath et al. (2014). Total herbage production (THP, kg DM ha^{-1}) was calculated as the sum of the herbage mass at the beginning of the stocking period and the total herbage accumulation along the stocking period (DHA x number of days of each subperiod). Residual biomass (RB, kg DM ha^{-1}) was evaluated after removing the animals from the experimental area at the end of the stocking period by collecting all the aboveground litter in five randomly located 0.25 m^2 quadrats per experimental unit.

2.3. Herbage intake by grazing animals

2.3.1. Herbage intake and fecal production

Dry matter intake (DMI) was estimated according to double n-alkane technique (Dove and Mayes, 2006). Two evaluation campaigns were made in each stocking period just before the SF_6 collections, aiming to compare enteric CH_4 emissions with herbage intake. After checking that all animals were grazing and well adapted to their respective paddocks, steers were orally dosed twice a day (07.30 and 15.30 h) with cellulose pellets (Carl Roth, GmbH, Karlsruhe, Germany) containing ~200 mg of dotriacontane (C32) for 10 consecutive days. The beginning dates of the evaluation campaigns were: 08/14/2013; 09/24/2013; 08/28/2014 and 09/30/2014. Fecal samples were collected before pellet administration two times a day during the last 5 days of the dosing procedure. These samples were collected, then placed in ziplock bags and frozen at −20 °C. At the end of collection period, the samples from each animal were thawed and homogenized, dried at 60 °C for 72 h, milled to pass through a 1-mm mesh, identified, and stored in plastic bags for subsequent analysis of n-alkanes (Johnson, 1978).

The analysis of n-alkanes in forage and feces followed the procedure suggested by Dove and Mayes (2006). The description and analysis of n-alkanes was performed by gas chromatography (GC) using a Shimadzu GC-2010 with same chromatograph conditions portrayed by Savian et al. (2014). The chromatographic peaks related to each alkane were identified employing the Shimadzu GC Solution software, and the description of the alkane chain was established with analogy between the external standard and corresponded retention time of each alkane and expressed in quantity of feces and forage in mg kg^{-1} of DM (Mayes et al., 1986).

Dry matter intake (DMI) was predicted after determining the amount of naturally occurring n-alkanes in the forage (C33) and their homologs (C32, orally dosed; De-Stefani Aguiar et al., 2013).

Fecal output was estimated according to the following equation:

Fecal production (kg DM per day) = Dose value of C32/(Fecal C32 - Forage C32).

2.3.2. Chemical composition

To evaluate n-alkane concentration in the pasture, 500 g herbage samples were collected by hand-plucking for each tester animal on the second and the third collection days (Halls, 1954). In addition, organic matter (OM, g kg^{-1} MS^{-1}), crude protein (CP, g kg^{-1} DM), neutral detergent fiber (NDF g kg^{-1} DM^{-1}), acid detergent fiber (ADF g kg^{-1} DM^{-1}) and the n-alkane profile were evaluated. The samples were analysed by the NIRS method, Perstorp analytical spectrometer, Silver Spring, MD based on a database of approximately 3000 samples conducted by The Walloon Agricultural Research Center, Belgium (Decruyenaere et al., 2009).

2.4. Animal performance

Experimental animals were crossbred Angus x Hereford x Nelore steers initially weighting 262 ± 4.9 kg and aged 14 months. The stocking period lasted 135 days, until November 6th. In 2014, stocking period began on June 2nd with an average sward height of 21.6 ± 2.1 cm and herbage mass of 1562 ± 164 kg DM ha^{-1}. Steers similar to those used in the first evaluation year were used, with an initial body weight of 237 ± 8.8 kg and 12 months of age on average, and the stocking period lasted until November 1st, totaling 152 days.

Animals were weighed at the beginning and at the end of the stocking period, after 12 h fasting from solids and liquids. Steers' average daily gain (ADG, g $animal^{-1}$ day^{-1}) was calculated using the same methodology as Kunrath et al. (2014). After the ADG determination, the number of days that each tester animal took to reach 450 kg LW was estimated (Days to 450 kg). This scenario represents the most frequently used beef cattle production system in southern Brazil, where steers are fattened in grazing systems until reaching the final live weight of 450 kg (Ferraz and de Felício, 2010). The stocking rate (SR, kg LW ha^{-1}) was also calculated using the same methodology as Kunrath et al. (2014).

2.5. CH_4 emissions

CH_4 emissions were evaluated using sulfur hexafluoride (SF_6) protocol (see Johnson et al., 1994) with adaptations (Gere and Gratton, 2010). Pre-calibrated permeation tubes containing SF_6 as tracer gas were implanted in animals' reticulum (*per os* dosing) with releases rates of 2.82 ± 0.34 mg day^{-1} (2013) and 3.62 ± 0.43 mg day^{-1} (2014). Evaluations were made 10 days after the tubes were placed.

The animals were adapted to sampling apparatus containing stainless steel cylinders (0.5 L) for collection connected to flow regulators (Gere and Gratton, 2010). The containers remained on the animals for 5 days (Pinares-Patiño et al., 2012). Two gas collections were made in 2013 (08/30 and 10/18), and three collections in 2014 (08/06, 09/13 and 10/28). The campaigns were made close as possible to DMI evaluations. Background CH_4 and SF_6 concentrations were collected in triplicate using the same apparatus, placed 1 m above ground level in the field.

Samples were analysed for concentrations of CH_4 and SF_6 were determined at the Laboratory of Biogeochemistry (Federal University of Rio Grande do Sul) by gas chromatography (Shimadzu, 2010; Japan) using flame ionization (250 °C) and electron capture (350 °C) detectors, respectively.

Methane emission was calculated using specific PR of SF_6 and the ratio between CH_4 and SF_6 collected after correction with background field gas concentrations (Johnson et al., 1994).

CH_4 emission was expressed in terms of g CH_4 $animal^{-1}$ day^{-1}. Other forms to express CH_4 emission were: g CH_4 per g of metabolic LW (g kg^{-1} $LW^{-0.75}$), g CH_4 g^{-1} DMI^{-1}, g CH_4 ha^{-1} day^{-1} (Eha, emission per hectare), and g CH_4 kg^{-1} ADG^{-1} (which is referred here as CH_4 emission intensity). Also, considering the number of days to reach 450 kg LW and Eha we simulated fattening-to-slaughter emissions (FSE, kg CO_2eq ha^{-1} $year^{-1}$) to assess steers' carbon footprint during the whole fattening period. The CO_2eq emission is a standard metric for comparing emissions of different GHGs. The amount of CO_2eq was obtained by multiplying CH_4 emission (kg ha^{-1} $year^{-1}$) by 28, which is its global warming potential (GWP) (IPCC, 2014).

2.6. Data analysis

Mixed models were used to analyse the effect of treatments in relation to the dependent variables. The models were tested using the likelihood ratio test and Akaike Information Criterion (AIC). All the models were based on the homogeneous Gaussian distribution satisfying the condition of normality of the residuals. When there were differences between treatments, a Tukey post-hoc test was performed on the averages ($\alpha = 0.05$). Data were analysed using R software (version 2.12.0, R Development Core Team, 2010).

3. Results

There was no interaction between years and treatments for pasture characteristics ($p > 0.05$), so stocking periods (2013 and 2014) were combined in further analyses.

3.1. Sward attributes

Pasture production varied in response to the treatments (Table 1). The actual sward heights (SH) were very close to the pre-established management targets in the grazed treatments (10, 20, 30 and 40 cm, $p < 0.0001$). Herbage mass (HM) was inversely proportional to grazing intensity ($p < 0.0001$), increasing from G10 to G40 and varying linearly with sward height ($\hat{Y} = 142.65 + 93.64x$; $R^2 = 0.91$). Daily herbage accumulation rate (DHA) and total herbage production (THP) did not differ between treatments ($p > 0.05$). Residual biomass (RB) at the end of the stocking period increased with sward height ($p < 0.0001$) with values ranging from 1.48 to 5.46 Mg ha^{-1} $year^{-1}$ from the highest to the lowest grazing intensity.

The nutritive value of herbage is presented in Table 2. Crude protein (CP) and neutral detergent fiber (NDF) were not different between the grazing intensities ($p > 0.05$). Acid detergent fiber (ADF) was lower for G10 compared to G40 treatment ($p = 0.01$). Dry

Table 1
Productive characteristics of mixed Italian ryegrass (*Lolium multiflorum* Lam.) and black oat (*Avena strigosa* Schreb.) pastures under different grazing intensities (G10, intense grazing; G20, moderate grazing; G30, moderate-light grazing; G40, light grazing) in the stocking period of a soybean-beef cattle integrated system.

Parameters	Grazing intensities[a]				SEM	*P*-value
	G10	G20	G30	G40		
SH	12.1 d	21.0 c	29.9 b	38.3 a	0.35	<0.0001
HM	1.20 c	2.31 b	2.86 b	3.68 a	0.079	<0.0001
DHA	41.79	48.99	49.81	44.06	2.32	0.5926
THP	7.64	8.73	8.83	8.25	0.31	0.5480
RB	1.48 d	3.60 c	4.44 b	5.46 a	0.12	<0.0001

SH, actual sward height (average of the stocking period, cm); HM, average herbage mass (Mg DM ha^{-1}); DHA, average daily herbage mass (kg DM ha^{-1} day^{-1}); THP, total herbage production (Mg DM ha^{-1}); RB, pasture residual biomass on soil surface at the end of the stocking period (Mg ha^{-1}); SEM, standard error of the mean. Different letters in the same line represent significant differences among treatments according to the Tukey test ($\alpha = 0.05$). Values presented are averages of two stocking periods (2013 and 2014).

[a] G10, G20, G30 and G40 correspond to the target sward heights of 10, 20, 30 and 40 cm, respectively.

matter digestibility (DMD) was greater in the G10 treatment ($p < 0.0001$).

3.2. Herbage intake

Data related to herbage intake are presented in Table 3. Average values of daily dry matter intake (DMI) were lower for intense grazing (G10) compared to the other treatments. In addition, animals in G10 showed a relatively low intake of ~1.9% LW, whereas animals in the G40 showed an intake close to 2.1% LW. Considering the DMI, steers consumed 22% less in G10 than in G40. Due to the lower DMI at G10, the NDF and ADF intake was also lower in this treatment, with reductions of up to 30% compared to the other treatments ($p < 0.001$, Table 3). Average daily intake for digestible dry matter did not differ ($p > 0.05$) between the grazing management targets, with an average of 4.34 kg DM day^{-1}. Fecal production differed between treatments ($p < 0.0001$, Table 3) with values ranging from 1.86 to 2.88 kg DM $animal^{-1}$ day^{-1} for G10 and G40 grazing intensities, respectively. On the other hand, fecal production per area was on average 87% higher for G10 and G20 compared to G40 ($p < 0.0001$, Table 3).

3.3. Animal performance and CH_4 emissions

Data related to animal performance and CH_4 emissions are presented in Table 4. Steers presented lower ADG for G10 compared to the other treatments. The results obtained for ADG in G10 treatment corresponded to an increase in fattening time of up to 60 days to reach 450 kg of LW when compared to the other treatments. SR increased linearly ($\hat{Y} = 1880.7 - 36.179x$; $R^2 = 0.88$) from the lowest to the highest grazing intensity, ranging from 519 to 1509 kg LW ha^{-1}.

CH_4 emissions were considerably different among grazing intensities (Table 4). Average daily CH_4 emissions differed ($p < 0.001$) between G40 and G30 (225 g $animal^{-1}$ day^{-1} on average) compared to G20 and G10 (181 g $animal^{-1}$ day^{-1} on average). CH_4 emission per kg of metabolic LW was lower ($p = 0.01$) in G10 than in G40. Similar response was observed for CH_4 kg^{-1} DMI^{-1}, with G10 presenting lower values compared to G30 and G40 ($p < 0.001$). Grazing intensification increased fattening-to-slaughter emissions (FSE) especially in G10, which emitted 2.5 times more than the average of the other treatments.

Table 2
Chemical composition of mixed Italian ryegrass (*Lolium multiflorum* Lam.) and black oat (*Avena strigosa* Schreb.) pastures under different grazing intensities (G10, intense grazing; G20, moderate grazing; G30, moderate-light grazing; G40, light grazing) in the stocking period of a soybean-beef cattle integrated system.

Parameters	Grazing intensities[a]				SEM	*P*-value
	G10	G20	G30	G40		
CP	218	212	203	194	4.45	0.2610
NDF	463	474	481	506	5.51	0.0562
ADF	235 b	249 ab	255 ab	268 a	3.39	0.0132
DMD	696 a	637 b	634 b	606 b	3.36	<0.0001

CP, crude protein (g kg^{-1} DM^{-1}); NDF, neutral detergent fiber (g kg^{-1} DM^{-1}); ADF, acid detergent fiber (g kg^{-1} DM^{-1}), DMD, dry matter digestibility (g kg^{-1} DM^{-1}); SEM, standard error of the mean. Different letters in the line represent significant differences among treatments according to the Tukey test ($\alpha = 0.05$). Values presented are averages of two stocking periods (2013 and 2014).

[a] G10, G20, G30 and G40 correspond to target sward heights of 10, 20, 30 and 40 cm, respectively.

Table 3
Steers' intake of mixed Italian ryegrass (*Lolium multiflorum* Lam.) and black oat (*Avena strigosa* Schreb.) pastures under different grazing intensities (G10, intense grazing; G20, moderate grazing; G30, moderate-light grazing; G40, light grazing) in the stocking period of a soybean-beef cattle integrated system.

Parameters	Grazing intensities[a]				SEM	*P*-value
	G10	G20	G30	G40		
DMI	5.98 b	6.90 a	7.09 a	7.31 a	0.10	<0.0001
DMI, %LW	1.86 b	2.05 ab	2.07 ab	2.12 a	0.0035	0.0442
CPI	1.26	1.44	1.52	1.45	0.04	0.4909
NDFI	2.75 b	3.28 ab	3.36 a	3.68 a	0.07	0.0005
ADFI	1.40 b	1.73 a	1.79 a	1.95 a	0.04	0.0003
DDMI	4.00	4.42	4.41	4.53	0.8	0.1325
FP $animal^{-1}$	1.86 c	2.53 ab	2.51 b	2.88 a	0.5	<0.0001
FP ha^{-1}	1263.1 a	1197.4 a	969.9 ab	657.3 b	10.31	<0.0001

DMI, dry matter intake (kg $animal^{-1}$ day^{-1}); CPI, crude protein intake (kg $animal^{-1}$ day^{-1}); NDFI, neutral detergent fiber intake (kg $animal^{-1}$ day^{-1}); ADFI, acid detergent fiber intake (kg $animal^{-1}$ day^{-1}); DDMI, digestible dry matter intake (kg $animal^{-1}$ day^{-1}); FP $animal^{-1}$, fecal production (kg $animal^{-1}$ day^{-1}); FP ha^{-1}, fecal production (kg ha^{-1} $year^{-1}$); SEM, standard error of the mean. Different letters in the line represent significant differences among treatments according to the Tukey test ($\alpha = 0{,}05$). Values presented are averages of two stocking periods (2013 and 2014).

[a] G10, G20, G30 and G40 correspond to target sward heights of 10, 20, 30 and 40 cm, respectively.

Table 4
Animal performance and CH_4 emissions of steers under different grazing intensities (G10, intense grazing; G20, moderate grazing; G30, moderate-light grazing; G40, light grazing) of mixed Italian ryegrass (*Lolium multiflorum* Lam.) and black oat (*Avena strigosa* Schreb.) in the stocking period of a soybean-beef cattle integrated system.

Parameters	Grazing intensities[a]				SEM	*P*-value
	G10	G20	G30	G40		
ADG	814 b	1088 a	1117 a	1101 a	14.28	<0.0001
Days to 450 kg	248 a	190 b	185 b	190 b	1.89	<0.0001
SR	1509 a	1078 b	819 c	519 d	29.95	<0.0001
CH_4 $animal^{-1}$	171 b	192 b	223 a	227 a	5.34	<0.0001
CH_4 kg^{-1}	2.30 b	2.42 ab	2.78 ab	2.86 a	0.14	0.0122
CH_4 DMI^{-1}	25.2 b	26.9 ab	29.9 a	30.6 a	1.02	0.0004
FSE	6617 a	3387 b	2974 bc	1952 c	65.07	<0.0001

ADG, average daily gain (g $animal^{-1}$ day^{-1}); Days to 450 kg, days to reach 450 kg of live weight considering the ADG; SR, stocking rate (kg LW ha^{-1}); CH_4 $animal^{-1}$, CH_4 emission per animal (g $animal^{-1}$ day^{-1}); CH_4 kg^{-1}, CH_4 emission per kg of metabolic LW (g kg^{-1} $LW^{-0.75}$); CH_4 DMI^{-1}, CH_4 emission per kg of dry matter intake (g kg^{-1} DMI^{-1}); FSE, fattening-to-slaughter CH_4 emission (kg CO_2eq ha^{-1} $year^{-1}$ to reach 450 kg LW); SEM, standard error of the mean. Different letters in the line represent significant differences among treatments according to the Tukey test ($\alpha = 0{,}05$). Values presented are averages of two stocking periods (2013 and 2014).

[a] G10, G20, G30 and G40 correspond to target sward heights of 10, 20, 30 and 40 cm, respectively.

A quadratic relationship between ADG and sward height was observed (Fig. 1), with an increase in animal performance up to 30 cm of SH ($\hat{Y} = -0.001x^2$ - $0.0599x$ + 0.2468; $R^2 = 0.73$). CH_4 emission intensity (CH_4 kg^{-1} ADG^{-1}) also presented a quadratic relationship ($\hat{Y} = 0.168x^2$ - $7.59x$ + 255.72; $R^2 = 0.58$), with the minimum value close to 23 cm, which represents 170 g CH_4 kg^{-1} ADG^{-1}.

Fig. 2 illustrates the trade-off between the two main results on a per area basis: daily LW gain per hectare (LWGha, kg LW ha^{-1} day^{-1}) had a negative linear relationship to sward height ($\hat{Y} = 5.47 - 0.09x$; $R^2 = 0.79$), as did emission per hectare (Eha, kg CO_2eq ha^{-1} day^{-1}; $\hat{Y} = 26.5 - 0.50x$; $R^2 = 0.86$). Regression analyses of LWGha and Eha were highly negatively correlated with sward height ($r = -0.89$ and $r = -0.92$, respectively; $p < 0.0001$).

4. Discussion

4.1. Sward characteristics and herbage intake

Grazing intensity is the management tool that truly drives system functioning and responses in ICLS. There was a 93.64 kg DM ha^{-1} increase in herbage mass for each cm increase in SH and 36.18 kg LW ha^{-1} decrease in stocking rate for each cm increase in SH. To sustain lower SH, a larger number of animals is necessary, resulting in higher herbage intake per unit area (Kunrath et al., 2014) but lower intake per animal.

Low pasture height is a limiting factor to bite mass formation because it affects bite depth (Laca et al., 1992). As a consequence, animals spend more time searching for forage, despite which they may still not ingest sufficient amounts under severely restricted situations (see DMI for G10, Table 3). On the other hand, excessively tall swards limit consumption by imposing greater difficulty to bite formation due to the dispersion of leaves and stems (Gordon and Benvenutti, 2006). This, however, was not a limiting factor in the studied situation, even at higher SH.

Grazing management resulted in differences in herbage quality (DMD, Table 2). These differences were buffered by total nutrient intake (DDMI, Table 3) because intense grazing limited the amount of nutrients consumed daily by the animals as a result of excessively short swards. Lower forage intake and animal nutritional status under high stocking densities are explained by lower forage availability (Stuth and Lyons, 1999), which influenced dung deposition by steers (McCollum and Galyean, 1985).

Grazing management strongly affects trade-off relationships among C and N coupling-decoupling cycles (Soussana and Lemaire, 2014). According to these authors, C and N cycles are coupled through plant growth and photosynthetic process until decomposition, when decoupling processes begin to take place. When crops and livestock are integrated, grazing becomes an important driver of nutrient decoupling, as a small portion of C and N constitute animal tissues and are exported from the area at the end of the stocking period, and the remainder returns to the environment. C returns mostly via dung (60%), whereas N returns mainly as urine (70%). Additional C losses (3–5% of digestible C) occur through CH_4 emissions from enteric fermentation (IPCC, 2006). Therefore, increasing grazing intensity will increase C and N decoupling, until the moment in which negative impacts caused by animals' grazing (decoupling) will exceed the benefits from soil-vegetation C–N coupling (Soussana and Lemaire, 2014).

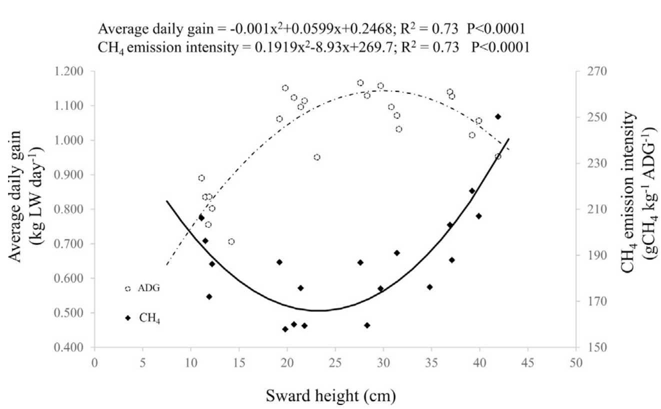

Fig. 1. Average daily live weight gain (ADG, kg LW day^{-1}) and CH_4 emission intensity (g CH4 kg^{-1} ADG^{-1}) in relation to average sward height of mixed black oat (*Avena strigosa* Schreb.) and Italian ryegrass (*Lolium multiflorum* Lam.) pasture in a soybean-beef cattle integrated system.

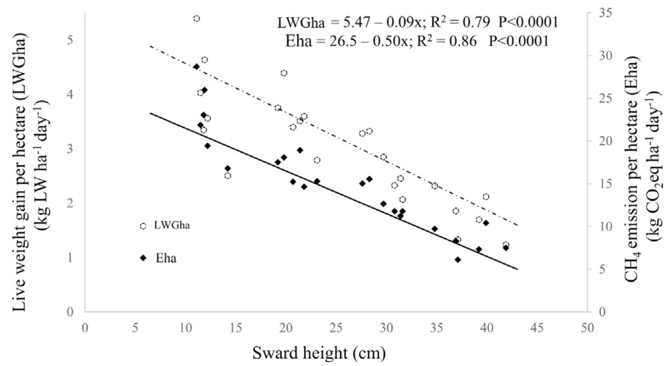

Fig. 2. Trade-off between animal performance and environmental impacts: daily live weight gain per hectare (LWGha) and CH_4 emission per hectare (Eha) by steers in relation to average sward height of mixed black oat (*Avena strigosa* Schreb.) and Italian ryegrass (*Lolium multiflorum* Lam.) pasture in a soybean-beef cattle integrated system.

Conversely, C and N re-coupling can be enhanced via shoot and root accumulation, leading to C sequestration in soil organic matter. Bayer et al. (2006) estimated that annual additions of 10–12 Mg DM ha^{-1} were needed to maintain or increase carbon stocks in no-tillage ungrazed systems in southern Brazil. Considering only litter deposition at the end of the stocking period (RB, Table 1), G20, G30 and G40 treatments contributed 30, 40 and 50% of that amount, respectively. Thus, grazing might seem to prevent the system from reaching its full potential or detract from the soil-building principles of no-till. However, long-term studies have shown that pastures grazed at moderate to light grazing intensities accumulate more biomass throughout the stocking period, and that residual litter does not represent the full extent of canopy dynamics in ICLS (Carvalho et al., 2018). Our THP results corroborate these observations. Furthermore, our study did not take into account soybean shoot dry matter addition, which was estimated by Assmann et al. (2014) as 5.2 Mg ha^{-1}, meaning that the requirements for dry matter additions previously stated would be surpassed even in the highest grazing intensity.

4.2. Animal performance and CH_4 emission

To successfully mitigate CH_4 emissions from the grass-fed livestock sector, increasing livestock performance (per animal and/or hectare) and crop/pasture productivity could provide multiple mitigation benefits, whether directly by improving GHG emission intensities or indirectly from benefits associated with land use sparing (Herrero et al., 2016).

Grazing management affects herbage utilization and, consequently, animal performance and CH_4 emissions. Animal production performance measured as ADG was 35% lower under intense grazing compared to the other treatments (Table 4). This result is explained mainly by lower herbage intake at the highest grazing intensity (Table 3). As an indicator of system performance, differences in the number of days required for each animal to reach the final live weight in the different treatments were due to the combined differences in the nutritional quality of the animals' diets and daily intake (Table 4). This result, besides increasing animals' lifetime CH_4 emissions due to late slaughter, could delay the sowing date of the following cash crop in the ICLS, as well as compromising the whole system's economic efficiency.

Lower daily CH_4 emissions in G10 and G20 (g CH_4 animal^{-1} day^{-1}, Table 4) could be associated with DMI and fiber intake (NDFI and ADFI), especially in G10 treatment. This scenario represents the classic positive correlation between herbage intake and CH_4 emissions (Kurihara et al., 1999). Furthermore, fermentation of plant cell walls (i.e., NDF) results in more CH_4 production compared with non-cell wall components (Johnson and Johnson, 1995).

Results for FSE (Table 4) were triggered by negative effects associated with high stocking rates (G10) (i.e., ADG and Days to 450 kg) that lead to a process of cascading damage amplification over time.

Prediction models with tropical grazing systems showed that the effect of SR on production efficiency was not linear, but increased up to an optimum SR and then decreased at higher SR (Howden et al., 1994). Similarly, ADG and CH_4 emission intensity (g CH_4 kg^{-1} ADG^{-1}) in our study had a curvilinear response to SH, with optimum values reached when pasture was managed between 30 and 23 cm height, respectively (Fig. 1).

LWGha was mostly driven by SR. This result is a consequence of high individual performance (ADG>0.800 g animal^{-1} day^{-1}) in all treatments, even at the highest grazing intensity, which could be associated with the high forage quality typical of southern Brazilian winter pastures. When we compare such results with those obtained on tropical pastures, we observe that annual live weight gains are lower compared to temperate pastures (Winter et al., 1991) and that individual responses have a higher share in LWGha than SR, as long as no overgrazing occurs. Applying the same rationale to emissions, we can hypothesize that higher emissions per ha from cattle grazing tropical pastures (Berndt and Tomkins, 2013) originate from changes in individual responses rather than the SR, while in temperate pastures the SR would play a key role.

We found a positive linear effect of grazing intensity (LWGha) and the associated environmental costs of land use. This trade-off is clear when both effects are analysed together. Each centimeter decrease in SH represents an additional liveweight gain of 90 g ha^{-1} day^{-1} but implies a cost of 500 g CO_2eq ha^{-1} day^{-1} (Fig. 2). In other words, the proportion of gain vs costs is 1 *vs* 5.5 (LWGha *vs* Eha) for each cm decrease in SH.

Intensification of grassland productivity by manipulation of both primary production and SR leads to complex responses in terms of environmental impacts, so that tradeoffs between production and environmental conservation should consider the existence of an “environmental carrying capacity” (Soussana and Lemaire, 2014). Our results show that increasing livestock production per area could be a risky option as it would lead to expanded nutrient losses through CH_4 emission in decoupled carbon cycles. This effect could cause an imbalance in the ratio of nutrient use to demand and lead to land degradation (e.g. lower carbon and nitrogen stocks under intense grazing, as verified in Assmann et al., 2014), potentially diluting the positive effects on beef production over time. However, we have identified a management threshold region between 23 and 30 cm of sward height where it is possible to optimize both environmental and productive outcomes.

4.3. Moving from farm scale to global GHG mitigation

It is possible to significantly reduce GHG emissions through grazing intensity adjustment. The attempt to intensify animal production through increased stocking rates leads to greater CH_4 emissions from enteric fermentation because it demands a larger number of animals per unit of area and more time to finish these animals until slaughtering. This combination can double CH_4 emissions in the system (see FSE, Table 4).

On the other hand, a simple stocking rate adjustment in order to maintain the sward heights between 23 and 30 cm could offset CH_4 emissions and improve animal performance in mixed black oat and Italian ryegrass pastures (Table 4). For this, the only required input is knowledge, and the tool to achieve these results is improved grazing management. That's where the practical applicability of our study resides.

Current Brazilian GHG inventories using country-specific Tier 2 methods establish enteric CH_4 emission as the product of number of animals and an emission factor (steers in Rio Grande do Sul = 45), corresponding to 990 kg CO_2eq^{-1} animal^{-1} year^{-1} (MCT, 2010). In this study, CH_4 emissions in units of CO_2eq were almost 25% lower (800 kg CO_2eq^{-1} animal^{-1} year^{-1}, average of all grazing intensities, data not shown). Consequently, the accurate determination of emission rates in different production scenarios and under different stocking rates is necessary at regional scale to adjust the parameters of input in national inventories.

More than a half of Brazilian pasture areas are degraded to some extent (de Oliveira Silva et al., 2017), which in southern Brazil is often related to overgrazing (Carvalho and Batello, 2009). A simple change in grazing management from intense grazing (G10) to moderate (G20) or moderate-light grazing (G30) in 50% of the total area designated to ICLS in Rio Grande do Sul could provide a reduction in emissions of up to 3.9–4.3 Tg CO_2eq year^{-1}. Scaling out this action within 5 years has the potential to achieve the mitigation of 13–14% of the target to GHG emissions from the whole agricultural sector and 22–25% of the target to enteric fermentation from the livestock sector (MCT, 2010) pledged by the Brazilian Government in the Paris Agreement (UNFCCC, 2015).

Despite the potential benefits of well-managed (moderate grazing intensity) ICLS for reducing CH_4 emissions, it is important to highlight that the impacts on all GHGs together should be considered to better estimate the outcome of the action (Robertson et al., 2000), which requires further studies. An additional consequence, and simultaneously an incentive for the adoption of this practice, is that increases in productivity and efficiency lead, in many cases, to increased profitability and cash flow in livestock farms. Understanding these tradeoffs is fundamental to reducing the environmental impacts of livestock production (Herrero and Thornton, 2013) and to balancing the co-benefits and tradeoffs necessary for its successful implementation (Smith et al., 2008).

5. Conclusion

Adequate grazing management is the key strategy to improve animal production and reduce the environmental impact from livestock in ICLS. Grazing management affects herbage utilization and, consequently, animal performance and CH_4 emissions. At the individual level, CH_4 emission and animal performance had optimal values when pasture height was managed within a range of 23–30 cm. At the farm level, we found a positive linear effect of grazing intensity on animal live weight gain per hectare and the associated environmental costs of land use.

Given that most producers graze pastures to very short heights, large-scale adoption of target heights within 23–30 cm in southern Brazil has the potential to achieve 13–14% of the mitigation target for GHG emissions from the whole agricultural sector and 22–25% of the target for enteric fermentation from the livestock sector pledged by the Brazilian Government in the Paris Agreement.

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