FORAGE BASED LIVESTOCK SYSTEMS

Pasture intensification in beef cattle production can affect methane emission intensity

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Abstract

Increasing greenhouse gas (GHG) emissions from anthropogenic activities have contributed to global warming and consequently to climate change. Among all sources of emissions, the agricultural sector accounts for just under a quarter, mainly because of the intensification of food production systems necessary to supply the growing demand of the population. As ruminal fermentation is the largest source of methane emission in the livestock industry, emission by cattle has become the focus of studies. The aim of this study was to evaluate enteric methane emission and emission intensities of Nelore cattle at different ages submitted to levels of intensification of the grazing system. Twenty-four animals per cycle (age of 21.8 and 13.1 mo in cycles 1 and 2, respectively) were randomly distributed across different grazing systems: irrigated pasture with a high stocking rate (IHS), dryland pasture with a high stocking rate (DHS), recovering dryland pasture with a moderate stocking rate (DMS), and degraded pasture with a low stocking rate (DP). Methane emission was measured using the sulfur hexafluoride technique in each season of the cycle. Intensive systems provided higher yields of good-quality forage as well as superior animal performance when compared with DP. Methane yields were different between seasons and cycles. Methane emissions per average daily weight gain and dry matter digestible intake were different between treatments. Differences in the results were observed when they were analyzed per hectare, with the highest gain yield ($P = 0.0134$), stocking rate, weight gain, carcass production, and total methane emission ($P < 0.0001$) being found for the intensive systems. There were no differences in emissions per weight gain or carcass production between production systems, while a difference was observed between cycles ($P = 0.0189$ and $P = 0.0255$, respectively), resulting in lower emission intensities for younger animals. We conclude that more intensive systems resulted in a higher kilograms production of carcass per hectare; however, animals at 19 mo of age raised in the IHS and DMS systems had a lower emission intensity in kilogram of CO_2 -eq. per kilogram of carcass. Moderate intensification (DMS) using animals at about 19 mo of age might be an effective strategy to mitigate GHG emissions from Brazilian tropical pastures. Further studies are needed to understand the relationship between increasing productivity and decreasing environmental impacts, especially methane emission from ruminants.

Key words: *Bos indicus*, enteric fermentation, grassland, Nelore, sulfur hexafluoride, sustainability

Abbreviations

ADF	acid detergent fiber
ADG	average daily weight gain
CARC	carcass production (kg ha ⁻¹)
CGY	carcass gain yield
CH ₄ ADG	CH ₄ emission per ADG (g kg ⁻¹)
CH ₄ CARC	CH ₄ emission per carcass weight (kg carc. ⁻¹ ha ⁻¹)
CH ₄ DMD	CH ₄ emission per dry matter digestible intake (g % ⁻¹)
CH ₄ DMI	CH ₄ emission per DMI (g kg ⁻¹)
CH ₄ GD	CH ₄ emission (g d ⁻¹)
CH ₄ LWa	CH ₄ emission per average live weight (g kg ⁻¹)
CH ₄ Mcal	CH ₄ emission (Mcal d ⁻¹)
CH ₄ MW	CH ₄ emission per metabolic weight (g kg ⁻¹)
CH ₄ WG	CH ₄ emission per weight gain (kg kg ⁻¹ ha ⁻¹)
CH ₄ Y	CH ₄ emission (kg ha ⁻¹)
CO ₂ CARC	CH ₄ emission per carcass weight (kg CO ₂ -eq. kg carc. ⁻¹ ha ⁻¹)
CP	crude protein
DHS	dryland pasture with a high stocking rate
DMI	dry matter intake
DMS	recovering dryland pasture with a moderate stocking rate
DMY	dry matter yield
DP	degraded pasture with a low stocking rate
EE	ether extract
FE	feed efficiency
GE	gross energy
GHG	greenhouse gas
HCW	hot carcass weight
IHS	irrigated pasture with a high stocking rate
IVDMD	in vitro DM digestibility
LW	live weight
MM	mineral matter
MW	metabolic weight
NDF	neutral detergent fiber
SRAE	average stocking rate per animal equivalent
SRAU	average stocking rate per animal unit
WG	weight gain (kg ha ⁻¹)
YM	CH ₄ yield (GE lost in the CH ₄ form in %).

Introduction

Brazil has one of the largest and most technologically advanced agricultural sectors in the world. Within this context, livestock farming plays an important role because of the vast areas of grazing lands (MCTI, 2016). Additionally, Zebu cattle, especially the Nellore breed, are well adapted to the tropical conditions and to the extensive grazing systems that predominate in the country (Sakamoto et al., 2014).

The growing world population will increase the global demand for food. The currently used extensive livestock production systems must be improved to meet the market requirements. Within this context, it is necessary to implement efficient exploitation of tropical pasture, including fertilizer application and intensive

management techniques. Intensive pasture management is preferred over traditional systems to improve both economic and environmental outcomes (Oliveira Silva et al., 2017). According to DeRamus et al. (2003), pasture intensification is the most efficient management practice in converting forage into meat and milk by cattle, as it reduces the enteric methane emission per unit of product. In addition, the use of appropriate and intensive pasture management techniques has the potential to mitigate methane and nitrous oxide emissions through the carbon fixation capacity of tropical soils, allowing the recovery of degraded pasture areas (Berndt and Tomkins, 2013; Oliveira, 2015).

Greenhouse gas (GHG) emissions from the livestock sector represent 14.5% of global anthropogenic emissions, caused by feed production, enteric fermentation, animal waste, and land-use change (FAO, 2017). The intensification of grazing management improves animal performance since the animals reach the ideal slaughter weight earlier or produce more meat, reducing the emission intensity of the production system (Eckard et al., 2010; Koscheck et al., 2020). Besides the indirect methane emission reduction, the advantages of pasture intensification are the standardization of forage production and better grazing control, with a consequent increase in the stocking rate and animal production per hectare (DeRamus et al., 2003). However, caution must be taken in the excessive use of fertilizers to avoid increased N₂O emissions (Soussana and Lemaire, 2014; Warner et al., 2016) and excessive stocking rates (Beauchemin et al., 2008). Although intensive production systems decrease methane emission intensities, they can increase N₂O and CO₂ emissions (Mazzetto et al., 2015). Therefore, a balance must be established when applying technologies that mitigate GHG emissions. According to Herrero et al. (2016), one solution to decrease agricultural emissions would be to reduce the demand for livestock products. However, this approach would have negative economic impacts on meat producers and be prejudicial to global health and food security. Oliveira Silva et al. (2016) reported that the intensification of beef production in the Cerrado biome, when decoupled from deforestation, would result in a 30% increase of current production by 2030, with a consequent reduction of up to 10% in GHG emissions.

Improved management of Canadian cow-calf production systems reduced the average emission intensity by up to 31% (Alemu et al., 2017). Simulation of different meat production scenarios showed that intensive systems could reduce emission intensity by up to 50% compared with extensive systems and relieve the pressure on forest and pasture areas (Mazzetto et al., 2015; Cardoso et al., 2016). Meat production, particularly beef, has been growing in Brazil due to improvements in the production process and professionalization of the livestock sector, increasing the production levels. Despite the advantages of intensive systems, GHG emissions, especially enteric methane emission, must be considered when the animals are ruminants. Gross emission of ruminal methane tends to follow the growth in cattle production since it is a natural and intrinsic process in ruminants. Brazil is one of the few Latin American countries that has invested in technologies for the in vivo measurement of enteric methane and for the evaluation of alternatives for mitigating the emission of this gas in livestock production (Benaouda et al., 2017). According to the FAO (2013), if producers in a given system, region, and climate adopted the practices applied by the 10% to 25% of producers with the lowest emission intensities on their properties, the emissions could be reduced by 18% to 30% (or 1.8 to 1.1 Gt of CO₂-eq).

The correct management of tropical pastures helps increase the soil's carbon sequestration capacity (Oliveira Silva et al., 2017). However, little is known about enteric methane emission in different tropical grazing systems (Cardoso et al., 2016). Despite the great diversity of livestock production systems, few studies have measured ruminal methane under field conditions (Canesin et al., 2014; Carvalho et al., 2016; Demarchi et al., 2016; Koscheck et al., 2020). Further research is necessary to obtain reliable results related to each region or farming system. Therefore, this study was conducted to evaluate ruminal methane emission and emission intensities of Nelore cattle at different ages submitted to different levels of intensification of the grazing system. The study hypothesis is that intensive pasture production systems reduce methane emission intensities of Nelore cattle, regardless of animal age.

Materials and Methods

Location and animals

The experiment was carried out from 2012 to 2015 at Embrapa Southeast Livestock, São Carlos, São Paulo State, Brazil (21°57'33.32"S, 47°50'33.28"W; altitude of 856 m). The animals were handled and managed according to the guidelines of the Institutional Animal Care and Use Committee (No. 05/2016; Brazilian Agricultural Research Corporation—EMBRAPA, Brazil). At the beginning of the experimental periods, animals from the experimental herd of Embrapa Southeast Livestock were selected from a group that was homogeneous in terms of body weight, age, and genetics and were randomly allocated to the different treatments. The study used 24 Nelore steers in each production cycle (cycle 1 = 337 d and cycle 2 = 361 d). The animal's age was 21.8 ± 0.6 and 13.1 ± 0.8 mo in cycles 1 and 2, respectively, and the initial body weight was 410 ± 32 and 251 ± 30 kg, respectively. The first production cycle lasted from September 2012 to August 2013 and the second from September 2013 to September 2014. The steers were raised exclusively on pasture, with mineral supplementation from weaning to slaughter.

Treatments and management

The treatments consisted of different types of pasture systems, with two repetitions in each area (Figure 1), as follows: intensively managed irrigated pasture with a high stocking rate (IHS), intensively managed dryland pasture with a high stocking rate (DHS), recovering dryland pasture with a moderate stocking rate (DMS), and degraded pasture with a low stocking rate (DP). The production systems (treatments) were classified according to the applied technologies, including fertilization, liming, grass species used, use of irrigation, stocking rate, and pasture management (rotational vs. continuous grazing). The DP system

was considered degraded due to the nonuse of technology. In this study, intensification refers to pasture improvements alone and is based on 100% forage-fed cattle.

The IHS and DHS pastures were established in 2002 with *Megathyrus* (*Panicum*) *maximum* Jacques (cv. Tanzania and Mombasa) and were managed under rotational grazing. The DMS and DP pastures were established in 1996 with *Urochloa* (*Brachiaria*) *brizantha* (Hochst ex A. Rich) Stapf (cv. Marandu) but they became infested with *Urochloa decumbens* Stapf (cv. Basilisk). The pastures in the DMS system underwent a recuperation process starting in 2011, which consisted of surface application of lime and general fertility correction. The pastures in DMS and DP were managed under rotational and continuous grazing, respectively.

Each area of the IHS and DHS treatments (1.75 ha) comprised 12 paddocks with rotational management of the animals (3 d of occupation and 33 d of rest). Nitrogen was applied as urea. The IHS pasture received five summer fertilizations of 80 kg N ha⁻¹ and five fertilizations of 40 kg N ha⁻¹ in the dry season (total of 600 kg N ha⁻¹). The DHS pasture received five summer fertilizations of 80 kg N ha⁻¹ (total of 400 kg N ha⁻¹). The dryland treatment areas with moderate stocking rates (3.3 ha each) comprised six paddocks with rotational management of the animals (6 d of occupation and 30 d of rest). The DMS area received five summer fertilizations of 40 kg N ha⁻¹ (total of 200 kg N ha⁻¹). Each area of the degraded treatment consisted of a single paddock (3.3 ha) with continuous grazing. Furthermore, no correction or fertilization was applied in the DP system. All pastures (except DP) were limed and fertilized with superphosphate and potassium chloride to achieve 20 mg dm⁻³ and 4% K for soil cation exchange capacity. The IHS system was oversown with viable pure seeds of *Avena strigosa* (60 kg ha⁻¹) and the ryegrass species *Lolium multiflorum* (30 kg ha⁻¹) on June 1, 2012 and April 22, 2013 according to Oliveira et al. (2005).

The stocking rate of all grazing systems was adjusted using the put-and-take technique (Mott and Lucas, 1952), according to forage availability in each paddock. Pasture management was adjusted based on the stubble height of the grass (30 cm for *Panicum* and 15 cm for *Urochloa*) according to Costa et al. (2004) and Costa and Queiroz (2017), except for the DP treatment. Additional animals (in addition to the testers—tracer animals used to measure performance and enteric methane) were used to adjust the stocking rate using the put-and-take technique. In general, intensification of beef cattle grazing systems is accompanied by on-pasture supplementation; however, in this study, only a commercial mineral supplement was given ad libitum in all treatments. In the rainy season, the mineral composition was 13.0% P, 21.4% Ca, 2.3% Mg, 4.0% S, 1.0% Zn, 0.35% Cu, 0.17% Mn, 0.03% Co, 0.03% I, 0.003% Se, and 0.13% F. In the dry season, the mineral supplement had the following composition: 1.2% P, 8.0% Ca, 3.5% Na, 0.2% Mg, 1.5% S, 0.64% Zn, 0.017% Cu, 0.013% Mn, 0.001% Co, 0.012% I, 0.0003% Se, 0.02% F, and 40.0% crude protein (CP). In all treatments, none of the supplements (except for minerals) were considered in the analysis.

Forage analysis and intake

Dry matter yield (DMY) (kg DM ha⁻¹) was calculated as the sum of forage accumulation per grazing cycle (30 d) in each season and production cycle evaluated. For the analysis of nutritional composition, forage samples were collected during the grazing cycles and methane emission was assessed to represent the respective season. Forage was sampled in three paddocks per area (three samples per area) of the rotational grazing systems

Figure 1. Treatments draft: IHS 600 kg N ha⁻¹ yr⁻¹ (12 paddocks each: C and D); DHS 400 kg N ha⁻¹ yr⁻¹ (12 paddocks each: E and F); DMS 200 kg N ha⁻¹ yr⁻¹ (6 paddocks each: G and H); DP 0 kg N ha⁻¹ yr⁻¹ (1 paddock each: I and J).

(IHS, DHS, and DMS) before the start of grazing. Four subsamples were collected randomly in each paddock. The samples were collected by cutting the forage (direct method) 30 cm above ground level in the IHS and DHS systems (*P. maximum*) or 15 cm above ground level in the DMS system (*U. brizantha*). Pasture management aimed to maintain a specific residue height for each grass species, which was applied to all systems, except for DP (Costa and Queiroz, 2017). In the DP system, only the tester animals were kept throughout the production cycle in the paddock, regardless of the pasture's residue height. The forage cutting height depends on the grass species used to form the pasture and the grazing behavior of the animals. Because of the decumbent growth habit of *Urochloa* sp., it is more appropriate to cut the grass close to the soil, whereas the grazing height of the animals should be considered for erect-growing grasses (*Panicum*) (Salman et al., 2006). In the DP pasture system (*U. decumbens*), the samples were collected from exclusion cages during continuous grazing, which prevents the animals from having access to the sampling site during the period of forage growth.

The four subsamples were dried in a forced ventilation oven at $60 \pm 5^\circ\text{C}$ for 72 h, weighed, and homogenized to obtain a composite sample for each area (partial DM). After drying, the *U. decumbens* and *U. brizantha* samples were analyzed to determine CP, mineral matter (MM), ether extract (EE), neutral detergent fiber (NDF), acid detergent fiber (ADF), and lignin content, as well as in vitro DM digestibility (IVDMD) using near-infrared spectroscopy. The spectra were obtained using a Fourier transform near-infrared spectrometer with a polarizing interferometer (BÜCHI, model NIRFlex N-500). A calibration model developed and validated by Embrapa Southeast Livestock was used to predict the chemical composition. This model was specifically developed for the analysis of species and cultivars of *Urochloa* spp. DM was determined by drying the samples for 24 h in an oven at 105°C . The partial and definitive DM content was used to calculate DM.

After drying at 65°C , the *P. maximum* samples were submitted to nutrient analysis to determine DM (method 934.01; AOAC, 1990), CP (method 920.87; AOAC, 1990), MM (method 923.03; AOAC, 1990), EE (method 920.85; AOAC, 1990), NDF, ADF, and lignin according to Goering and Van Soest (1970). The IVDMD of organic matter was determined by the modified method of Moore and Mott (1974). Gross energy (GE) was analyzed using a calorimetric pump (C200 System, IKA, Staufen, Germany).

Dry matter intake (DMI, kg DM d^{-1}) was estimated using the equation proposed by Azevêdo et al. (2010). This equation was developed for beef cattle production systems in Brazil, with $R^2 = 0.758$:

$$\text{DMI} = -2.7878 + (0.08789 \cdot \text{LW}^{0.75}) + (5.0487 \cdot \text{ADG}) - (1.6835 \cdot \text{ADG}^2),$$

where DMI, dry matter intake; LWa, average live weight; ADG, average daily weight gain.

Animal performance

The same amount of forage was available for all animals under rotational grazing (put-and-take method). Six animals were used per treatment, with three animals per repetition in the pasture area. All animals were weighed in each grazing cycle without fasting (about 30 d), always at the same time of day.

At the beginning and end of the experimental period, the animals were weighed (initial live weight [LWi] and final live weight [LWf]) after 16 h of dry fasting. The total duration of the experiment was 337 and 361 d for cycles 1 and 2, respectively.

The average daily weight gain (ADG) of the animals in each season was calculated by dividing the total gain by the number of days of each season. Feed efficiency (FE) was estimated by dividing daily gain by daily intake. In addition, the metabolic weight (MW) was determined as follows: $\text{MW} = \text{LW}^{0.75}$.

The average weight gain per hectare (WG) and the carcass gain per hectare (CARC) of the animals in the treatments were calculated considering the experimental period. The stocking rates were calculated per hectare considering the following animal unit (AU) = 450 kg/AU:

$$\text{SRAU} = \text{AU/ha.}$$

The average stocking rate considered the animal equivalent (AE) as the average weight of the animals in the batch:

$$\text{SRAE} = \text{AE/ha.}$$

The animals were slaughtered at an average age and LW of 32.9 and 25.5 mo, and 562 ± 47 and 439 ± 45 kg, in cycles 1 and 2, respectively, in a commercial cattle slaughterhouse. After slaughter, the hot carcass weight (HCWf) was recorded. The HCW at the beginning of the experiment (HCWi) was predicted by regression analysis using the SAS PROC REG's stepwise tool (SAS Institute, Inc., Cary, NC), as described by Berndt et al. (2017). The data set used to develop the prediction equation consisted of 64 Nelore animals with an average LW of 396 kg (Berndt et al., 2017). Using the abovementioned approach, the prediction equation was built as $\text{HCWi} = -23.4847 + (0.6350 \times \text{LW})$, which provided an R^2 of 0.96 and Cp of -0.74 . The carcass gain yield (CGY) was calculated to assess how much of the weight gain was converted to carcass. For this purpose, the carcass gain ($\text{HCWf} - \text{HCWi}$) was divided by body weight gain ($\text{LWf} - \text{LWi}$) multiplied by 100. The average CGY of the treatments was 50.7% and 53.9% in cycles 1 and 2, respectively. Thus, it was possible to calculate the methane emission intensity in kilogram $\text{CO}_2\text{-eq.}$ per kilogram carc. based on the following model:

$$\text{CO}_2\text{CARC} = \frac{(x \cdot 21)}{y},$$

where CO_2CARC is the emission intensity in kilogram $\text{CO}_2\text{eq.}$ /kilogram carc.; x is the total methane emission in kilograms during the experimental period; 21 is the CH_4 global warming potential in CO_2 equivalent; and y is the total carcass weight gain in kilograms during the experimental period. The global warming potential of 21 for methane was chosen because this value was used in Brazilian National Inventories until 2018, following the recommendations of the United Nations Framework Convention on Climate Change (UNFCCC).

Ruminal methane measurement

For methane collection, the sulfur hexafluoride (SF_6) gas tracer technique developed by the University of Washington (Johnson and Johnson, 1995) and refined by Berndt et al. (2014) was used. This technique is consolidated (Boadi et al., 2002) and can be reliably applied in studies comparing treatment effects (Pinares-Patiño and Clark, 2008), especially for grazing animals (McGinn et al., 2006). The technique uses a permeation tube or capsule administered to the animal and deposited in the rumen. These capsules were calibrated and prepared especially for the current experiment. There was a constant average emission of SF_6 gas of $2.396 \pm 0.06 \text{ mg d}^{-1}$ in the first cycle and of $1.753 \pm 0.19 \text{ mg d}^{-1}$ in the second cycle.

Before the start of the sampling period, the animals (24 per cycle) were adapted to the polyvinyl chloride sampling devices (evacuated sampling canisters and halters) for at least 15 d. Methane gas was collected for five consecutive days, with the evacuated sampling canisters being changed every 24 h. The gas expelled through the mouth and nostrils of the animals was aspirated under vacuum with a capillary tube fixed in a halter and connected to a canister (collector), which was supported on the neck of the animal. After each sampling period, the evacuated canisters were sent for chromatographic analysis, and their content was diluted with pure nitrogen to determine the quantities of SF_6 and CH_4 gases. Polyvinyl chloride canisters were kept in the same environment as the animals to measure the background concentrations of CH_4 and SF_6 during the sampling period. The background concentrations of CH_4 and SF_6 measured by chromatography in the “blank readings” were subtracted from the concentrations found in the evacuated sampling canisters of the animals.

Sampling took place four times per year during the months representative of the four seasons. The evaluation periods were October 1 to 7, 2012 (spring), January 21 to 27, 2013 (summer), April 22 to 28, 2013 (autumn), and July 29 to August 4, 2013 (winter) for animals in cycle 1. In cycle 2, the following periods were evaluated: December 2 to 8, 2013 (spring), April 2 to 8, 2014 (summer), June 9 to 15, 2014 (autumn), and August 11 to 17, 2014 (winter).

A GHG chromatograph (Shimadzu GC-2014, Kyoto, Japan) was used for the analysis of CH_4 and SF_6 . The concentration of the CH_4 and SF_6 collected in the evacuated sampling canisters was determined with a flame ionization detector and an electron capture detector, respectively. The chromatography analysis was carried out immediately after the end of the field sampling periods in the laboratory of Embrapa Southeast Livestock, permitting the reuse of the evacuated sampling canisters in the subsequent sampling period.

Methane-related variables

The animal's CH_4 emissions were determined in g per day (CH_4GD) by chromatography. These values were then used to calculate CH_4 emissions per animal in relation to average live weight (CH_4LW), metabolic weight (CH_4MW), average daily weight gain (CH_4ADG), dry matter intake (CH_4DMI), and dry matter digestible intake (CH_4DMD). All variables (LW, MW, ADG, and DMI) were obtained considering the mean values calculated for each season within the experimental period for each production cycle. Energy losses through enteric CH_4 emissions were also calculated for each treatment in each season and cycle as the loss of energy in megacalories per animal per day (CH_4Mcal) and as the percentage of GE intake lost as CH_4 per animal ($\text{CH}_4\text{yield} = \text{YM}$).

Considering the different levels of intensification evaluated in the four production systems, CH_4 emissions per hectare were calculated: per cycle (CH_4Y), and per average weight gain (CH_4WG), as well as in g of CH_4 per g carcass (CH_4CARC) and in kilogram of CO_2 -eq. per kilogram carcass (CO_2CARC).

Statistical analysis

The data were analyzed using the SAS program (SAS Institute, Inc., Cary, NC). First, normality testing of residuals (Shapiro-Wilk) was performed using PROC UNIVARIATE, to check for outliers at a 5% level of significance. The pasture variables were analyzed as a completely randomized design in a split-split-plot arrangement, with paddock as plot, cycle as subplot,

and season as sub-subplot using a mixed model (PROC MIXED) that included the fixed effects of treatment ($i = 1, \dots, 4$), season ($j = 1, \dots, 4$), cycle ($k = 1, 2$), treatment * season, treatment * cycle, season * cycle, and treatment * season * cycle, and random effects of paddock and cycle * paddock, adjusting the (co)variance structure of repeated measures in the same experimental unit (“cycle * paddock”).

For performance and enteric methane variables, a completely randomized design in a split-plot arrangement, with animal as plot and season as subplot, was analyzed using a PROC MIXED that included the fixed effects of treatment ($i = 1, \dots, 4$), season ($j = 1, \dots, 4$), cycle ($k = 1, 2$), treatment * season, treatment * cycle, season * cycle, and treatment * season * cycle, adjusting the (co)variance structure of repeated measures in the same experimental unit (“animal”).

The residual (co)variance structures for each variable were chosen based on the lowest value of the corrected Akaike information criterion according to Wang and Goonewardene (2004). The variables calculated per hectare were analyzed using mixed models (PROC MIXED) that included the fixed effects of treatment ($i = 1, \dots, 4$), cycle ($j = 1, 2$), and treatment * cycle, and the random effect of area repetition.

Means were fitted by the least squares method (LSMEANS) and compared, if necessary, based on the probability of difference (PDIFF) using the t-test. Pearson correlations were estimated between CH_4GD and the variables LWa, ADG, and DMI. Statistical significance was declared when $P < 0.05$.

Results

Forage analysis

Animal performance and enteric methane emissions are directly dependent on the quantity and quality of the forage ingested. Hence, differences were observed in the average nutritional values of the pastures of the production systems during the seasons of the two experimental periods (Figure 2). Differences were found for all variables, except for EE ($P = 0.1354$) and GE ($P = 0.0531$) between treatments, and the results were expected considering the different levels of intensification of the grazing systems, using the application of fertilizer doses. There was no difference in DM ($P = 0.0514$) and GE ($P = 0.5875$) between seasons, and in DM ($P = 0.0688$) and IVDMD ($P = 0.7392$) between production cycles (Figure 2). Regardless of the degree of intensification of the pasture systems, positive effects on MM, CP, NDF, ADF, IVDMD, and DMY were observed compared with the DP system. On the other hand, the best result of lignin was obtained for the least technified systems (DMS and DP). More relevant differences between the treatments in the winter season were observed for EE, CP, AFD, lignin, ADF, IVDMD, and GE (Figure 2).

Triple effects of the interaction between treatment, season, and cycle were observed for DM ($P = 0.0073$), MM ($P = 0.0146$), EE ($P < 0.0001$), CP ($P = 0.0315$), lignin ($P < 0.0001$), and IVDMD ($P = 0.0030$) (Figure 2). The definition of the different pasture intensification levels was based on the forage and pasture management used. On the one hand, *Panicum* pastures produce more mass per hectare and forage quality is better; however, they demand higher soil fertility, fertilization, and good management and are commonly used in more intensive production systems. On the other hand, *Urochloa* is more rustic and resistant, better supporting eventual management failure and less intense production. To compare different production systems, we also evaluated forages with different production potentials.

Figure 2. Herbage chemical composition from production systems with different levels of intensification during seasons (spring, summer, autumn, and winter) of the two production cycles. The figures show: (a) DM, (b) MM, (c) EE, (d) CP, (e) NDF, (f) ADF, (g) lignin, (h) IVDMD, (i) GE, and (j) DMY, in cycle 1: 337 d and average age of 27.4 mo and cycle 2: 361 d and average age of 19.3 mo, in production systems.

Animal performance

Differences in the animals' performance were observed between the intensification levels of the grazing systems, seasons, and production cycles (Table 1). Animals of the IHS, DMS, and DHS treatments exhibited greater LWf, MW, and DMI compared with those of the DP system. Likewise, the average ADG also indicated

poorer performance by animals in the DP system, due to the low performance in the winter season (Table 1). In the winter season, the daily weight gain of the animals in the DP system was 0.149 and 0.062 kg in cycles 1 and 2, respectively, and 0.150 kg in cycle 2 for animals of the DHS treatment. The animals exhibited higher ADG and FE and lower DMI in cycle 2 compared with those of cycle 1 in the spring, summer, and autumn seasons.

The intensification of grazing systems allowed a higher stocking rate, thus increasing productivity. Table 3 shows the differences between treatments for stocking rate, WG, CGY, and CARC during the experimental period. The highest and lowest values were observed for the IHS and DP systems, whereas the DHS and DMS systems showed similar results for WG and CARC. The analysis of the production results of the IHS system showed 4.0-, 4.3-, and 5.7-times higher average stocking rate per animal unit (SRAU), WG, and CARC, respectively, in cycle 1, and 5.7-, 8.5-, and 9.1-times higher values in cycle 2 when compared with the DP system.

Ruminal methane measurement

The average methane production was 198 and 179 g CH₄ day⁻¹ in cycles 1 and 2, respectively, and did not differ between treatments. Higher methane emissions were reported for both cycles in the autumn season and for cycle 1 in the winter season in all treatments. Among the other methane emission variables, a difference between treatments was observed for CH₄ADG, CH₄DMD (Table 2), and CH₄Y (Table 3). Season and cycle effects were observed in all variables (Table 2). In all treatments, animals of cycle 1 exhibited lower emission intensities demonstrated by CH₄LWa, CH₄MW, CH₄DMI, CH₄DMD, and YM compared with those of cycle 2, except in the winter season.

The simple correlation coefficients obtained for CH₄GD were 0.50 ($P < 0.0001$) with LWa, 0.17 ($P = 0.020$) with ADG, and 0.57 ($P < 0.0001$) with DMI. An average energy of 7.8% and 9.7% was lost as methane in cycles 1 and 2, respectively, with lower values for the IHS and DMS systems in cycle 2 (Table 2).

We found no differences in CH₄LWa or CH₄MW (Table 2), although the LWa and MW of the animals differed between treatments (Table 1). There was a difference in DMI between treatments (Table 1). Despite the lack of a difference in CH₄DMI, emissions tended to be lower for the IHS and DMS systems in cycle 2 (Table 2). The simple correlation coefficient between CH₄GD and DMI (0.57), which was higher than the correlation between CH₄GD and LWa (0.50), confirms the strong relationship between CH₄ emission and DMI. In this study, a large dispersion and low R^2 (0.34) were observed between CH₄GD and DMI (Figure 3).

Although CH₄Y was higher in the intensified systems during the experimental period, CH₄WG, CH₄CARC, and CO₂CARC did not differ between treatments, with higher production of kilograms product in these systems compared with DP (Table 3). Differences in these variables were observed between production cycles, with lower methane emission intensities for younger and lighter animals.

Discussion

Forage analysis

Differences were found between the pasture managements tested (Figure 2), in agreement with studies that have assessed tropical pastures composition (Santos et al., 2008; Sousa et al., 2010). Paciullo et al. (2016) reported that the more N is applied

Table 1. Performance from Nellore steers grazing different pastures with different levels of intensification during the experimental period

Cycle ¹	Treatment	Season ²	Variables				
			LWf, kg	MW, kg ^{0.75}	ADG, kg	DMI, kg	FE, %
1	IHS	SPR	483 ^{Ad(A)}	99.2 ^{Ad(A)}	0.58 ^{Aa(A)}	8.07 ^{Ab(A)}	6.93 ^{ABa(B)}
		SUM	513 ^{Ac(A)}	105 ^{Ac(A)}	0.33 ^{Ab(B)}	7.92 ^{Ab(A)}	4.05 ^{Bb(B)}
		AUT	564 ^{Ab(A)}	112 ^{Ab(A)}	0.57 ^{Aa(A)}	9.34 ^{Aa(A)}	6.50 ^{Aa(A)}
		WIN	603 ^{Aa(A)}	119 ^{Aa(A)}	0.58 ^{Aa(A)}	9.95 ^{Aa(A)}	6.15 ^{Aa(B)}
	DHS	SPR	451 ^{Ad(A)}	94.7 ^{Ad(A)}	0.42 ^{ABab(B)}	7.37 ^{ABc(A)}	5.90 ^{Ba(B)}
		SUM	486 ^{ABc(A)}	101 ^{ABc(A)}	0.37 ^{Ab(B)}	7.70 ^{Ac(A)}	4.82 ^{ABa(B)}
		AUT	529 ^{ABb(A)}	107 ^{ABb(A)}	0.52 ^{ABa(A)}	8.60 ^{Bb(A)}	5.07 ^{Aa(B)}
		WIN	561 ^{BCa(A)}	113 ^{Ba(A)}	0.47 ^{Aab(A)}	9.11 ^{Ba(A)}	5.30 ^{Aa(A)}
	DMS	SPR	459 ^{Ad(A)}	96.5 ^{Ad(A)}	0.39 ^{Bb(B)}	7.38 ^{ABc(A)}	5.26 ^{Ba(B)}
		SUM	495 ^{Ac(A)}	102 ^{Ac(A)}	0.39 ^{Ab(B)}	7.90 ^{Ac(A)}	4.97 ^{ABa(B)}
		AUT	536 ^{Ab(A)}	108 ^{Ab(A)}	0.44 ^{Bb(B)}	8.63 ^{Bb(A)}	5.27 ^{Aa(B)}
		WIN	576 ^{ABa(A)}	115 ^{ABa(A)}	0.60 ^{Aa(A)}	9.63 ^{ABa(A)}	6.65 ^{Aa(A)}
	DP	SPR	414 ^{Bd(A)}	87.7 ^{Bd(A)}	0.53 ^{Aa(A)}	7.10 ^{Bb(A)}	8.13 ^{Aa(A)}
		SUM	457 ^{Bc(A)}	95.2 ^{Bc(A)}	0.46 ^{Aa(A)}	7.51 ^{Ab(A)}	6.37 ^{Aab(B)}
		AUT	497 ^{Bb(A)}	102 ^{Bb(A)}	0.45 ^{Ba(A)}	8.27 ^{Ba(A)}	5.76 ^{Ab(B)}
		WIN	507 ^{Ca(A)}	106 ^{Ca(A)}	0.15 ^{Bb(A)}	7.15 ^{Cb(A)}	1.77 ^{Bc(A)}
2	IHS	SPR	299 ^{ABd(B)}	66.7 ^{Ad(B)}	0.64 ^{Aa(A)}	5.59 ^{Ac(B)}	14.3 ^{Aa(A)}
		SUM	345 ^{Bc(B)}	75.8 ^{Bc(B)}	0.51 ^{Bb(A)}	6.02 ^{Bc(B)}	9.50 ^{Bb(A)}
		AUT	392 ^{Bb(B)}	84.2 ^{Bcb(B)}	0.51 ^{Bab(A)}	6.73 ^{Bb(B)}	8.27 ^{Bb(A)}
		WIN	448 ^{Aa(B)}	92.5 ^{Aa(B)}	0.61 ^{Aab(A)}	7.77 ^{Aa(B)}	8.73 ^{Ab(A)}
	DHS	SPR	320 ^{BCd(B)}	70.5 ^{Ad(B)}	0.66 ^{Ab(A)}	5.79 ^{Ac(B)}	13.9 ^{Aa(A)}
		SUM	392 ^{Ac(B)}	82.2 ^{Ac(B)}	0.80 ^{Aa(A)}	7.37 ^{Aa(A)}	14.3 ^{Aa(A)}
		AUT	445 ^{Ab(B)}	92.5 ^{Ab(B)}	0.57 ^{ABb(A)}	7.67 ^{Aa(B)}	8.38 ^{Bb(A)}
		WIN	459 ^{Aa(B)}	97.8 ^{Aa(B)}	0.15 ^{Cc(B)}	6.53 ^{Bb(B)}	2.05 ^{Cc(B)}
	DMS	SPR	320 ^{Ad(B)}	69.7 ^{Ad(B)}	0.73 ^{Aa(A)}	6.13 ^{Ab(B)}	15.8 ^{Aa(A)}
		SUM	369 ^{ABc(B)}	80.2 ^{ABc(B)}	0.54 ^{Bb(A)}	6.47 ^{Bb(B)}	9.42 ^{Bb(A)}
		AUT	434 ^{Ab(B)}	89.7 ^{ABb(B)}	0.70 ^{Aa(A)}	7.80 ^{Aa(B)}	10.7 ^{Ab(A)}
		WIN	467 ^{Aa(B)}	97.8 ^{Aa(B)}	0.35 ^{Bc(B)}	7.37 ^{ABa(B)}	4.77 ^{Bc(A)}
	DP	SPR	279 ^{Bc(B)}	65.0 ^{Ad(B)}	0.40 ^{Bb(B)}	4.65 ^{Bc(B)}	9.07 ^{Ba(A)}
		SUM	325 ^{Cb(B)}	72.5 ^{Bc(B)}	0.51 ^{Ba(A)}	5.69 ^{Bb(B)}	10.2 ^{Ba(A)}
		AUT	378 ^{Ba(B)}	81.2 ^{Cb(B)}	0.57 ^{ABa(A)}	6.68 ^{Ba(B)}	9.78 ^{ABa(A)}
		WIN	385 ^{Ba(B)}	86.5 ^{Ba(B)}	0.06 ^{Cc(A)}	5.08 ^{Cc(B)}	1.00 ^{Cb(A)}
SEM ³			6.44	1.10	0.01	0.10	0.28
			P-value				
Treatment			0.0002	0.0002	<.00001	<0.0001	0.0148
Season			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Cycle			<0.0001	<0.0001	0.0013	<0.0001	<0.0001
Treatment * Season			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Treatment * Cycle			0.0605	0.0453	0.0679	0.1132	0.0406
Season * Cycle			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Treatment * Season * Cycle			<0.0001	<0.0001	<0.0001	0.0002	<0.0001

¹Cycle 1, 337 d and average age of 27.4 mo; cycle 2, 361 d and average age of 19.3 mo.

²SPR, springer; SUM, summer; AUT, autumn; WIN, winter.

³Standard error of least squares means.

A–C, a–d Means followed by the same lowercase letter for season effect within treatment and those followed by the same uppercase letter for treatment effect in the same season within the column in each cycle are similar ($P > 0.05$) by the t-test. Means followed by the same uppercase letter between parentheses for each year season and treatment are similar ($P > 0.05$) by the t-test.

to pasture, the higher is the CP content of forage. The same was observed by Sousa et al. (2010) who applied different doses of N and P to *P. maximum* pastures. The CP content found here for the DP system, which was managed without the application of inputs or other technologies, was higher than those reported in the literature (Santos et al., 2008; Dalchiavon et al., 2017). This difference can be explained by the better condition of the experimental pasture compared with most degraded pastures in Brazil.

The use of irrigation along with the highest N dose in the IHS system resulted in more significant effects on MM and CP in cycle 2, in addition to greater DMY compared with the others (Figure 2). Irrigation of Mombasa grass exerted no effects on

CP and NDF levels but increased the DM availability (Palieraqui et al., 2006). Likewise, irrigation also did not affect the chemical composition or IVDMD of Mombasa grass (Ribeiro et al., 2010).

The difference observed in lignin content (Figure 2) can be explained by plant age and by differences between the grasses used. The lignin, NDF, and ADF content of *U. decumbens* increases as the plant grows older, while the CP and IVDMD content decreases (Paciullo et al., 2001). Castro et al. (2010) found no difference in lignin content for *P. maximum* of different ages; however, older plants had lower levels of CP and NDF. In the present study, the levels of CP, ADF, NDF, and IVDMD were higher in the intensified systems compared with the degraded system, a fact ruling out a possible influence of plant age on lignin

Table 2. Methane yields from Nellore steers grazing different pastures with different levels of intensification during the experimental period

Cycle ¹	Treatment	Season ²	Variables							
			CH ₄ GD, g d ⁻¹	CH ₄ LW, g kg ⁻¹	CH ₄ MW, g kg ⁻¹	CH ₄ ADG, g kg ⁻¹	CH ₄ DMI, g kg ⁻¹	CH ₄ DMD, g kg ⁻¹	CH ₄ Mcal, g % ⁻¹	YM, %
1	IHS	SPR	192 ^{Ab(A)}	0.40 ^{A(A)}	1.94 ^{Ab(A)}	354 ^{Ab(A)}	25.5 ^{A(A)}	46.2 ^{Ab(A)}	2.55 ^{Ab(A)}	7.76 ^{Ab(A)}
		SUM	155 ^{Ac(A)}	0.30 ^{Ab(B)}	1.47 ^{Ac(A)}	548 ^{A(A)}	18.9 ^{Ab(B)}	32.1 ^{Ab(B)}	2.06 ^{Ac(A)}	6.26 ^{Ac(B)}
		AUT	263 ^{Ab(A)}	0.47 ^{Ab(A)}	2.35 ^{Ab(A)}	458 ^{Ab(A)}	30.2 ^{Ab(A)}	50.3 ^{Ab(A)}	3.49 ^{Ab(A)}	10.2 ^{Ab(A)}
		WIN	254 ^{Ad(A)}	0.42 ^{Ab(A)}	2.14 ^{Ab(A)}	488 ^{Ab(A)}	27.1 ^{Ab(A)}	44.9 ^{Ab(A)}	3.38 ^{Ab(A)}	8.78 ^{Ab(A)}
	DHS	SPR	164 ^{Ab(A)}	0.36 ^{Ab(B)}	1.74 ^{Ab(B)}	391 ^{Ab(A)}	22.9 ^{Ab(B)}	42.8 ^{Ab(B)}	2.18 ^{Ab(B)}	7.53 ^{Ab(B)}
		SUM	149 ^{Ab(A)}	0.31 ^{Ac(B)}	1.48 ^{Ab(B)}	423 ^{Ab(A)}	19.3 ^{Ac(B)}	34.0 ^{Ab(B)}	1.99 ^{Ab(A)}	6.36 ^{Ac(B)}
		AUT	240 ^{Ab(A)}	0.45 ^{Ab(B)}	2.24 ^{Ab(B)}	534 ^{Ab(A)}	28.8 ^{Ab(B)}	48.6 ^{Ab(B)}	3.18 ^{Ab(A)}	9.36 ^{Ab(B)}
		WIN	249 ^{Ad(A)}	0.44 ^{Ab(A)}	2.21 ^{Ab(A)}	541 ^{Ab(B)}	28.1 ^{Ab(A)}	49.0 ^{Ab(A)}	3.31 ^{Ac(A)}	9.27 ^{Ab(A)}
	DMS	SPR	166 ^{Ac(A)}	0.36 ^{Ab(B)}	1.72 ^{Ab(A)}	436 ^{Ab(A)}	22.6 ^{Ab(B)}	38.2 ^{Ab(B)}	2.20 ^{Ac(A)}	7.04 ^{Ab(B)}
		SUM	153 ^{Ac(A)}	0.31 ^{Ab(B)}	1.49 ^{Ab(B)}	400 ^{Ab(A)}	19.3 ^{Ab(B)}	29.8 ^{Ac(B)}	2.03 ^{Ac(A)}	6.30 ^{Ab(B)}
		AUT	239 ^{Ab(A)}	0.45 ^{Ab(B)}	2.21 ^{Ab(B)}	544 ^{Ab(A)}	28.2 ^{Ab(B)}	44.2 ^{Ab(B)}	3.18 ^{Ab(A)}	8.92 ^{Ab(B)}
		WIN	271 ^{Ad(A)}	0.47 ^{Ab(A)}	2.37 ^{Ab(A)}	413 ^{Ab(A)}	30.4 ^{Ab(A)}	45.5 ^{Ab(B)}	3.60 ^{Ab(A)}	9.29 ^{Ab(A)}
	DP	SPR	119 ^{Bc(A)}	0.29 ^{Bc(B)}	1.36 ^{Bc(B)}	233 ^{Bc(B)}	18.3 ^{Bc(B)}	36.4 ^{Bc(B)}	1.58 ^{Bc(A)}	5.96 ^{Bb(B)}
		SUM	152 ^{Ab(A)}	0.33 ^{Ab(B)}	1.60 ^{Ab(B)}	372 ^{Bc(A)}	21.2 ^{Ab(B)}	32.7 ^{Ab(B)}	2.03 ^{Ab(A)}	6.46 ^{Ab(B)}
		AUT	221 ^{Ad(A)}	0.45 ^{Ab(B)}	2.17 ^{Ab(B)}	467 ^{Ab(A)}	28.2 ^{Ab(B)}	45.6 ^{Ab(B)}	2.94 ^{Ab(A)}	8.76 ^{Ab(B)}
		WIN	197 ^{Bb(A)}	0.39 ^{Bb(B)}	1.85 ^{Ab(A)}	746 ^{Ab(A)}	24.1 ^{Ab(A)}	49.6 ^{Ab(B)}	2.62 ^{Ab(A)}	7.95 ^{Ab(A)}
2	IHS	SPR	130 ^{Bb(B)}	0.44 ^{Ab(A)}	1.95 ^{Ch(A)}	207 ^{Bb(A)}	29.2 ^{Bb(A)}	46.6 ^{Ab(A)}	1.73 ^{Bb(B)}	9.17 ^{Ab(A)}
		SUM	138 ^{Ab(A)}	0.40 ^{Bb(B)}	1.82 ^{Bb(A)}	273 ^{Ab(B)}	25.6 ^{Bb(A)}	39.8 ^{Ch(A)}	1.84 ^{Ab(B)}	8.03 ^{Bb(A)}
		AUT	198 ^{Bb(B)}	0.50 ^{Ab(A)}	2.34 ^{Ab(A)}	391 ^{Ab(A)}	31.9 ^{Ab(A)}	48.0 ^{Ab(A)}	2.62 ^{Ab(A)}	10.4 ^{Ab(A)}
		WIN	155 ^{Ab(B)}	0.35 ^{Ac(A)}	1.67 ^{Ac(B)}	275 ^{Ch(B)}	22.4 ^{Ac(A)}	38.9 ^{Ab(A)}	2.06 ^{Ab(B)}	7.21 ^{Ab(B)}
	DHS	SPR	178 ^{Ab(A)}	0.56 ^{Ab(A)}	2.53 ^{Ab(A)}	272 ^{Ab(A)}	37.2 ^{Ab(A)}	61.1 ^{Ab(A)}	2.36 ^{Ab(A)}	12.2 ^{Ab(A)}
		SUM	181 ^{Ab(A)}	0.47 ^{Ab(A)}	2.23 ^{Ab(A)}	226 ^{Ac(B)}	32.0 ^{Ab(A)}	51.8 ^{Ab(A)}	2.41 ^{Ab(A)}	10.4 ^{Ab(A)}
		AUT	266 ^{Ad(A)}	0.60 ^{Ad(A)}	2.88 ^{Ad(A)}	479 ^{Ab(A)}	38.5 ^{Ad(A)}	60.0 ^{Ad(A)}	3.53 ^{Ad(A)}	12.4 ^{Ad(A)}
		WIN	167 ^{Ab(B)}	0.37 ^{Ab(A)}	1.72 ^{Ac(B)}	1,077 ^{Ab(A)}	22.7 ^{Ac(B)}	45.9 ^{Ab(A)}	2.22 ^{Ab(B)}	7.82 ^{Ac(A)}
	DMS	SPR	144 ^{Bc(A)}	0.45 ^{Bb(A)}	2.08 ^{Ch(A)}	199 ^{Bc(B)}	31.1 ^{Ab(A)}	47.4 ^{Ab(A)}	1.92 ^{Bc(A)}	9.62 ^{Ab(A)}
		SUM	148 ^{Ac(A)}	0.41 ^{Bb(A)}	1.86 ^{Bb(A)}	286 ^{Ab(B)}	25.9 ^{Ac(A)}	46.7 ^{Ab(A)}	1.97 ^{Ac(A)}	8.04 ^{Ab(A)}
		AUT	243 ^{Ad(A)}	0.56 ^{Ab(A)}	2.72 ^{Ab(A)}	346 ^{Bb(B)}	37.3 ^{Ab(A)}	57.4 ^{Ab(A)}	3.22 ^{Ab(A)}	11.0 ^{Ab(A)}
		WIN	183 ^{Ab(B)}	0.40 ^{Ab(B)}	1.88 ^{Ab(B)}	516 ^{Ab(A)}	24.7 ^{Ac(B)}	65.4 ^{Ab(A)}	2.43 ^{Ab(B)}	7.53 ^{Ab(B)}
	DP	SPR	157 ^{Ab(A)}	0.55 ^{Ab(A)}	2.37 ^{Ab(A)}	394 ^{Ab(A)}	34.9 ^{Ab(A)}	60.4 ^{Ab(A)}	2.09 ^{Ab(B)}	10.9 ^{Ab(A)}
		SUM	168 ^{Ab(A)}	0.51 ^{Ab(A)}	2.29 ^{Ab(A)}	344 ^{Ab(A)}	32.8 ^{Ab(A)}	58.7 ^{Ab(A)}	2.23 ^{Ab(A)}	9.96 ^{Ab(A)}
		AUT	236 ^{Ab(A)}	0.61 ^{Ad(A)}	2.87 ^{Ad(A)}	422 ^{Ab(A)}	39.5 ^{Ad(A)}	67.0 ^{Ad(A)}	3.13 ^{Ab(A)}	12.0 ^{Ab(A)}
		WIN	171 ^{Ab(A)}	0.44 ^{Ac(A)}	1.96 ^{Ac(A)}	934 ^{Ab(A)}	27.0 ^{Ac(A)}	70.8 ^{Ad(A)}	2.27 ^{Ab(A)}	8.48 ^{Ac(A)}
SEM ³		3.86	0.01	0.04	15.3	0.51	0.88	0.05	0.16	
			P-value							
Treatment			0.1216	0.1821	0.3186	<0.0001	0.2825	0.0007	0.1226	0.0783
Season			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Cycle			0.0036	<0.0001	<0.0001	0.0280	<0.0001	<0.0001	0.0035	<0.0001
Treatment * Season			0.0054	0.0058	0.0058	<0.0001	0.0053	<0.0001	0.0055	0.1434
Treatment * Cycle			0.0023	0.0049	0.0052	0.0001	0.0098	<0.0001	0.0022	0.0102
Season * Cycle			<0.0001	<0.0001	<0.0001	0.0013	<0.0001	0.0022	<0.0001	<0.0001
Treatment * Season * Cycle			0.0360	0.0511	0.0645	<0.0001	0.0638	0.0053	0.0364	0.2925

¹Cycle 1, 337 d and average age of 27.4 mo.; cycle 2, 361 d and average age of 19.3 mo.²SPR, springer; SUM, summer; AUT, autumn; WIN, winter.³Standard error of least squares means.A-C-B-C=Means followed by the same lowercase letter for season effect within treatment and those followed by the same uppercase letter for treatment effect in the same season within column in each cycle are similar ($P > 0.05$) by the t-test. Means followed by the same uppercase letter between parentheses for each year season and treatment are similar ($P > 0.05$) by the t-test.

Table 3. Performance and methane emissions per hectare from Nellore steers grazing different pastures with different levels of intensification during the experimental period

Variables	Cycle ¹	Treatments				SEM ²	P-value ³		
		IHS	DHS	DMS	DP		T	C	T * C
SRAU	1	6.91 ^{Aa}	5.16 ^{Ab}	4.03 ^{Ac}	1.73 ^{Ad}	0.718	<0.0001	0.0006	0.0461
	2	6.20 ^{Ba}	3.17 ^{Bb}	2.52 ^{Bc}	1.09 ^{Ad}	0.705			
SRAE	1	6.22 ^{Ba}	4.89 ^{Ab}	3.71 ^{Ac}	1.73 ^{Ad}	0.632	<0.0001	0.0108	0.0020
	2	8.99 ^{Aa}	4.65 ^{Ab}	3.49 ^{Ac}	1.57 ^{Ad}	1.031			
WG	1	1,034 ^{Ba}	713.8 ^{Ab}	551.6 ^{Ab}	238.9 ^{Ac}	110.7	<0.0001	0.0006	0.0026
	2	1,839 ^{Aa}	885.5 ^{Ab}	731.4 ^{Ab}	216.8 ^{Ac}	224.1			
CGY	1	55.20 ^{Aa}	53.60 ^{Aa}	52.05 ^{Aa}	41.95 ^{Bb}	2.129	0.0134	0.0707	0.2350
	2	54.65 ^{Aa}	54.40 ^{Aa}	56.05 ^{Aa}	50.60 ^{Aa}	1.114			
CARC	1	571.1 ^{Ba}	381.4 ^{Ab}	287.0 ^{Bb}	100.4 ^{Ac}	65.13	<0.0001	0.0002	0.0024
	2	1,004 ^{Aa}	482.2 ^{Ab}	410.2 ^{Ab}	109.9 ^{Ac}	122.8			
CH ₄ Y	1	480.0 ^{Aa}	325.0 ^{Ab}	252.9 ^{Ab}	98.72 ^{Ac}	52.83	0.0010	0.7293	0.2136
	2	504.8 ^{Aa}	332.7 ^{Ab}	226.5 ^{Ac}	102.9 ^{Ad}	56.18			
CH ₄ WG	1	0.474 ^{Aa}	0.456 ^{Aa}	0.459 ^{Aa}	0.415 ^{Aa}	0.023	0.4188	0.0189	0.0808
	2	0.276 ^{Bb}	0.376 ^{Aab}	0.310 ^{Bb}	0.476 ^{Aa}	0.030			
CH ₄ CARC	1	0.857 ^{Aa}	0.852 ^{Aa}	0.884 ^{Aa}	1.006 ^{Aa}	0.061	0.1259	0.0255	0.5570
	2	0.505 ^{Ab}	0.692 ^{Aab}	0.552 ^{Ab}	0.949 ^{Aa}	0.071			
CO ₂ CARC	1	17.99 ^{Aa}	17.88 ^{Aa}	18.56 ^{Aa}	21.12 ^{Aa}	1.279	0.1252	0.0253	0.5557
	2	10.59 ^{Ab}	14.53 ^{Aab}	11.58 ^{Ab}	19.92 ^{Aa}	1.481			

¹Cycle 1, 337 d and average age of 27.4 mo; cycle 2, 361 d and average age of 19.3 mo.

²Standard error of least squares means.

³T, treatment effect; C, cycle effect.

^{A,B,a-d}Means followed by the same lowercase letter within a row and those followed by the same uppercase letter within a column for each cycle are similar ($P > 0.05$) by the t-test.

Figure 3. Scatter plot of correlation between DMI and CH₄GD.

content (Figure 2). Despite the higher average DMY (Figure 2) in the IHS and DHS systems that could increase forage leftovers, the variable stocking management was performed correctly using regulatory animals.

Veloso (2012) found a higher lignin content for *P. maximum* treated with doses of 100 kg N ha⁻¹ yr⁻¹ or higher. This result was accompanied by an increase in CP and a decrease in NDF, which consequently improved digestibility, as observed here in cycle 2 (Figure 2). For *Urochloa*, the lignin content found was higher (5.0%) than that reported by Martins et al. (2013) (3.9%) and Mauri et al. (2015) (4.4%). For *P. maximum*, in the present study, lignin content was lower in cycle 1 (4.9%) and higher in cycle 2 (8.8%) when compared with Castro et al. (2010) (6.2%) and Ribeiro et al. (2010) (6.3%). Lower levels of lignin in *Panicum*

were found in simulated grazing samples (Balsalobre et al., 2003; Simili et al., 2007). Simili et al. (2007) and Ribeiro et al. (2010) reported a higher lignin content of Mombasa grass compared with Elephant grass samples. The present findings suggest that this difference in lignin content in cycle 2 is due to the difference in the grass species used. Overall, these findings show that the different N doses positively affected the nutritional composition of the forage, regardless of the difference in lignin content in cycle 2.

Differences in the nutritional composition of the diet in grazing systems and in the feeding behavior of cattle may affect emissions (Moraes et al., 2014). Hammond et al. (2009) reported that only 13% of the variation in CH₄ emission can be explained by the forage composition, while the individual digestive characteristics of animals and the interactions with the physical and chemical forage components exert a greater effect on this variation. In a study conducted on *U. brizantha* cv. Marandu pasture, Demarchi et al. (2016) found differences in nutrient analyses and enteric methane emissions between seasons, suggesting that the nutritional composition of the pasture may affect these emissions, as observed here. Likewise, Warner et al. (2017) concluded that the CH₄GD of dairy Holstein-Friesian cows submitted to different intake levels decreases with the improvement of the nutritional value and chemical composition of grass silage. Although Menezes et al. (2016) who studied feedlot Nellore bulls at 20 mo of age receiving diets with 10%, 12%, and 14% CP observed no differences in CH₄GD, the present study found lower CH₄GD for the IHS system in cycle 2 when the CP content was 15% (Figure 2 and Table 2), in agreement with the results of Warner et al. (2017). These findings highlight the importance of further studies investigating the relationship of the chemical composition of the diet with CH₄GD.

Animal performance

These performance results were expected considering the difference observed in forage characteristics among all treatments. Animals grazing on degraded pastures tend to lose weight during the dry period of the cycle, as observed here. Additionally, these animals emit methane without producing meat. This difference in ADG was also reported by [Demarchi et al. \(2016\)](#) for Nellore cattle assessed in different seasons. The animals of cycle 2 raised in the intensified systems gained more weight daily when compared with animals of the DP system and animals of cycle 1. This difference in gain can be explained by the growth curve of the animals according to age (13 vs. 21 mo). This curve tends to slow down as the animal reaches maturity and ages ([Owens et al., 1993](#)). Mature animals present lower muscle growth rates, since the total weight gain of the animal, in its majority, is composed of adipose tissue, which is directly relevant to the meat and carcass quality. Better productive results can be achieved with the efficient use of forage in production systems associated with other management factors, including sanitary, reproductive, and environmental factors, particularly GHG emissions ([Pereira et al., 2015](#)).

The effect of greater pasture intensification, including irrigation, in the IHS system was more pronounced on animal weight gain (average 6.3-fold increase) than on stocking rate (average 4.6-fold increase) compared with the DP system ([Table 3](#)). In contrast, [Ribeiro et al. \(2008\)](#) reported that irrigation had a greater impact on the stocking rate, that is, it influences biomass production more than forage digestibility. The stocking rate increases due to the intensification of the beef cattle production system, with a consequent increase in LW gain and carcass production per hectare ([Cardoso et al., 2016](#)). The IHS system resulted in 1.6-, 2.1-, and 6.5-fold higher production of kilograms carcass compared with the DHS, DMS, and DP systems, respectively ([Oliveira et al., 2018](#)). Management strategies that improve FE or productivity by using better forage and high-yield animals can reduce CH₄ emissions per unit of product ([Patra, 2012](#); [Oliveira Silva et al., 2017](#)).

Increasing animal productivity is one of the most effective ways of GHG mitigation, as it allows to reduce the number of animals necessary for the production of the same amount of product (meat or milk; [Hristov et al., 2013b](#)). Likewise, productivity can be increased through better pasture management ([Hristov et al., 2013b](#)). The findings reported here suggest that systems with some intensification levels are more productive, in addition to providing greater CGY compared with DP ([Table 3](#)). However, measurement of GHG emission is necessary when these technologies are used in pasture production systems in order to determine which intensification level is appropriate, considering the balance between animal productivity and GHG emission. Another important strategy to mitigate enteric methane emission is the use of animals with a higher production potential ([Koscheck et al., 2020](#)). In this study, animals of cycle 2 (average age of 19 mo) exhibited greater carcass gain ([Table 3](#)) because of higher ADG ([Table 1](#)) when compared with older animals (cycle 1).

Ruminal methane measurement

[Demarchi et al. \(2016\)](#) evaluated Nellore animals with an average weight and age of 393 kg and 23 mo, respectively, grazing on *U. brizantha* cv. Marandu pasture. These authors reported a lower daily methane emission (154 g CH₄ d⁻¹) compared with that observed here (198 and 179 g CH₄ d⁻¹ in cycles 1 and 2, respectively). [Demarchi et al. \(2016\)](#) observed higher enteric

methane emission in the summer season (221 g CH₄ d⁻¹), and our findings reported high emissions in the winter season in cycle 1 (243 g CH₄ d⁻¹) and autumn season in both cycles (238 and 236 g CH₄ d⁻¹ for cycles 1 and 2, respectively). These results may be related to the higher DMI. Comparison of methane emission in grams per day is not sufficient to explain the differences because animals can emit similar amounts of methane; however, one animal may lose weight in a degraded system and another may gain weight in an irrigated system. It is, therefore, important to compare emission intensities, that is, methane emission variables related to live weight, weight gain, intake, and carcass production.

In contrast to the present study, some authors found greater differences in enteric methane emissions of animals submitted to pasture intensification ([Jose Neto et al., 2015](#); [Koscheck et al., 2020](#)). One explanation is the application of supplementation, which is a characteristic of intensive grazing systems and was not used in this study. Integrated crop–livestock–forestry systems using two nitrogen levels were assessed by [Pontes et al. \(2018\)](#). Using grazing heifers, the authors found no treatment effect on CH₄GD or CH₄LWa. Nonetheless, they reported differences in methane emission per hectare as an outcome of indirect performance (stocking rate), similar to the findings reported here ([Tables 2 and 3](#)). Pasture intensification ensures a higher stocking rate, thus increasing CH₄GD per hectare ([Koscheck et al., 2020](#)).

GE intake lost as methane (YM) ranges from 2.0% to 11.6%, with this variation mainly depending on the animal's weight and diet composition [Johnson, D. E. 1992. Modelling global methane from livestock: biological and nutritional control. Final Report to NASA. Unpublished. Colorado State University, Department of Animal Sciences, Fort Collins; p. 80.](#) In ruminants, energy losses commonly range from 5.5% to 6.5% [Johnson, 1992, Unpublished report.](#) According to [Johnson and Ward \(1996\)](#), YM rates over 7% can occur when restricted amounts of high-quality diets or below the maintenance energy requirement are provided, which could explain the result obtained for the systems. [Fiorentini et al. \(2014\)](#) evaluated different dietary fatty acid profiles and observed lower YM values (3.05% to 4.81%). [Demarchi et al. \(2016\)](#) calculated an average annual YM of 6.3%, and [Nascimento et al. \(2016\)](#) reported values ranging from 6.18% to 9.02% when assessing the methane emission of Nellore animals fed *U. brizantha* hay cut at different stages of plant growth. The average YM of 7.8% and 9.7% found here in cycles 1 and 2, respectively, is higher than the values reported in the literature. This difference may be due to the quality of the forage across the production cycles.

On the one hand, [Nascimento et al. \(2016\)](#) reported CH₄LWa and CH₄MW values of 0.34 g CH₄ kg LWa⁻¹ and 1.51 g CH₄ kg MW⁻¹, respectively, which were lower than those found in this study (0.39 and 0.47 g CH₄ kg LW⁻¹ and 1.89 and 2.19 g CH₄ kg MW⁻¹ in cycles 1 and 2, respectively). On the other hand, [Canesin et al. \(2014\)](#) observed higher CH₄MW (2.53 g CH₄ kg MW⁻¹). Enteric methane emission is associated with DMI and LW of the animals, but diet composition interferes with this relationship ([Beauchemin et al., 2008](#)). The present study reported a CH₄GD of 198 and 179 g CH₄ d⁻¹ for animals with LWa of 489 and 355 kg and DMI of 8.23 and 6.46 kg DM d⁻¹ in cycles 1 and 2, respectively. Other studies on Nellore animals showed CH₄GD of 135 g CH₄ d⁻¹ for animals with LWa of 402 kg and DMI of 5.54 kg DM d⁻¹ ([Nascimento et al., 2016](#)), of 244 g CH₄ d⁻¹ for animals with LWa of 399 kg and DMI of 7.76 kg DM d⁻¹ ([Canesin et al., 2014](#)), and of 154 g CH₄ d⁻¹ for animals with LWa of 393 kg and DMI of 7.17 kg DM d⁻¹ ([Demarchi et al., 2016](#)).

Beauchemin and McGinn (2006), Hristov et al. (2013a), and Jonker et al. (2016) demonstrated a strong relationship between CH_4 emission and DMI based on a coefficient of determination (R^2) ranging from 0.82 to 0.86 for these variables. Coefficients (R^2) of 0.56 and 0.23 were reported by Grainger et al. (2007) and Savian et al. (2014), respectively.

This relationship between emission and feed intake can also be seen in Mercadante et al. (2015). These authors classified the animals according to residual feed intake and found that the more efficient animals consumed, on average, 1.03 kg DM d^{-1} less feed and emitted 19 g CH_4 d^{-1} less methane than the inefficient animals. According to Buddle et al. (2011), DMI is the main factor driving methane production in ruminants. However, CH_4DMI (g CH_4 / kg DMI) decreases with increasing DMI, which can be explained by the greater ruminal turnover that reduces diet digestibility.

Some studies reported results that demonstrated the effects of pasture quality on methane emission (Richmond et al., 2015; Warner et al., 2016). According to Clark et al. (2011), increasing forage digestibility may be an option to mitigate CH_4 emissions in pasture-raised livestock since the higher the feed digestibility, the lower the amount of energy lost by the animal in the form of methane. Results of CH_4DMI in the winter season of cycle 2 reported here confirm this, unlike Demarchi et al. (2016) who observed a higher CH_4DMI in the summer season with greater digestibility. Likewise, diet containing soybean reduced digestibility and methane emission in Nellore bulls finished in feedlot. (Rossi et al.,

2017). Although the feed digestibility affects the methane emission, observing these results, the DMI may have a greater relationship with the enteric methane emission. This may explain the results found here because animals in the DP system with low digestibility consumed less, but there were no significant differences in CH_4GD compared with the other systems ($P = 0.1216$). However, IVDMD was lower, and NDF and ADF were higher for DP (Figure 2). According to Hristov et al. (2013b), an increase in the quality or digestibility of the forage increases the production efficiency. Consequently, the emission intensity (CH_4CARC and CO_2CARC) can be reduced, as observed here (Table 3).

Likewise, pasture intensification can decrease emission intensity because of the increase in the quantity of meat produced, diluting the amount of emitted CH_4 . According to Soussana and Lemaire (2014), sustainable pasture intensification should always seek the maximization of three factors (considering the animal, plant, and soil), that is, a balance between the ingested C and returned to the soil, between the quality of forage/increase of digestibility and enteric CH_4 emission, and between the animal stocking rate and minimization of CH_4 and N_2O emissions from urine and nitrate leaching.

Intensive beef production systems require less time and area to obtain the final product, thus avoiding deforestation of new areas for production (Mazzetto et al., 2015; Cardoso et al., 2016). This intensification can be achieved through the improvement of pastures and animal husbandry practices. These two factors directly affect the emission intensity from the system,

Figure 4. Carcass production (a), methane emission (b), and emission intensity per hectare (c) of Nellore steers with an average age of 27 (cycle 1) and 19 (cycle 2) mo submitted to different levels of intensification of the grazing system.

potentially reducing GHG emissions per unit of product by 2% to 57% (Mazzetto et al., 2015).

According to Oliveira (2015) and Oliveira Silva et al. (2016), the recovery of degraded pastures has the greatest potential for mitigating GHG emissions through carbon sequestration in soils. The intensification of tropical pastures for beef production allows to store more C in soils compared with degraded pasture (Segnini et al., 2019). In some ecosystems, the natural fertility of the soil is low, and plant primary production is limited. However, with the application of lime and fertilizers to agricultural lands, pasture, or planted forests, primary production could significantly exceed that of the native vegetation (Boddey et al., 2012). Pasture soil carbon stocks can increase by 15% compared with the average soil carbon stocks of native vegetation (Assad et al., 2013); however, what is known is that soil C sequestration will cease some years after a management change when a new steady state is achieved (Smith, 2014). With regard to enteric methane, the difference in emission between production systems is related to the composition of the herd, particularly the larger number of cows and the shorter lifespan of animals until slaughter (Mazzetto et al., 2015; Cardoso et al., 2016). Dick et al. (2015) estimated CH_4LW_a values that were 60% lower for intensive systems compared with extensive beef production systems because of the better performance of animals raised on good-quality pasture.

The emission intensities in relation to carcass production reported here were not different. The DP system exhibited a trend of higher emission than the intensified systems ($P = 0.1259$ or $P = 0.1252$). In cycle 2, the degree of intensification (IHS and DMS) had an impact on CH_4CARC and CO_2CARC compared with the DP system. Under these conditions, this result indicates that, to reduce emission intensities in kilogram CO_2 -eq. kilogram carc. $^{-1}$, the investment does not have to be high and that a well-managed *Urochloa* pasture (P, K, and 200 kg N ha $^{-1}$) can provide the same methane emission per kilogram product for animals with an average age of 19 mo. The same result was not observed for older animals (cycle 2). Thus, moderate intensification (DMS) might be a more easily achievable and an equally, or even more, effective strategy to mitigate GHG emissions from Brazilian tropical pastures.

The livestock sector can substantially reduce GHG emissions through productivity improvements that reduce emission intensities, carbon sequestration through improved pasture management, and better livestock integration in the local bioeconomy (FAO, 2017). Animals with an average age of 19 mo exhibited a lower emission intensity (14.16 kg CO_2 -eq. kg carc. $^{-1}$) than animals at 27 mo of age (18.89 kg CO_2 -eq. kg carc. $^{-1}$). This finding can be explained by the difference in average carcass production (335 vs. 502 kg in cycles 1 and 2, respectively) per hectare between the production cycles evaluated, as there was no difference in average total methane emission per hectare (67.4 vs. 64.6 kg CH_4 in cycles 1 and 2, respectively; Figure 4).

In general, a difference between treatments was only observed for CH_4ADG and CH_4Y . The emission intensities exhibited a trend or difference within each season and production cycle evaluated. The benefits of well-managed pastures must be considered, including increased meat production per hectare and the consequent decrease in emission intensity in relation to carcass production as an effect of animal slaughter at a younger age. Therefore, a balance in the use of intensive technologies in pasture production systems is necessary to increase forage quality and productivity and to minimize environmental impacts, particularly GHG emissions by ruminants.

Conclusions

Well-managed and intensive pasture-based beef cattle production systems (IHS) can produce up to 9.1 times more kilograms of carcass per hectare. Animals with an average age of approximately 19 mo have a higher carcass production capacity than animals with an average age of 27 mo. Considering exclusively enteric methane emission, it was not possible to differentiate the most intensive grazing systems. A positive trend for the IHS and DMS systems compared with the DP system was only observed for emission intensity per kilogram of product. Animals with an average age of 19 mo had a lower emission intensity per kilogram of product. Further studies using technologies for intensification of pasture-based production systems of beef cattle of different ages are necessary to determine the balance between increasing productivity and minimizing environmental impacts through lower methane emission intensities of ruminants.

Acknowledgments

We would like to thank EMBRAPA Southeast Livestock team for conducting the project, EMBRAPA for financing the PECUS network (01.10.06.0001.05.00), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior-EMBRAPA (15/2014), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (88882.157051/2017-01) for the scholarship, Conselho Nacional de Desenvolvimento Científico e Tecnológico for the financial support (562861/2010-6), and Fundação de Amparo à Pesquisa do Estado de São Paulo for granting post-doctoral scholarship to L.S.S. (grant 2018/17313-5).

Conflict of interest statement

The authors declare no conflicts of interest regarding the publication of this article.

Literature Cited

- Alemu, A. W., B. D. Amiro, S. Bittman, D. MacDonald, and K. H. Ominski. 2017. Greenhouse gas emission of Canadian cow-calf operations: a whole-farm assessment of 295 farms. *Agric. Syst.* 151:73–83. doi:10.1016/j.agsy.2016.11.013
- AOAC. 1990. *Official methods of analysis*. 15th ed. Arlington (VA): Association of Official Analytical Chemists.
- Assad, E. D., H. S. Pinto, S. C. Martins, J. D. Groppo, P. R. Salgado, B. Evangelista, E. Vasconcellos, E. E. Sano, E. Pavão, R. Luna, et al. 2013. Changes in soil carbon stocks in Brazil due to land use: paired site comparisons and a regional pasture soil survey. *Biogeosciences* 10:6141–6160. doi:10.5194/bg-10-6141-2013
- Azevêdo, J. A. G., S. C. Valadares Filho, D. S. Pina, R. F. D. Valadares, and E. Detmann. 2010. Prediction of dry matter intake by beef cattle in feedlot. In: de Campos Valadares Filho, S., Marcondes, M. I., Chizzotti, M. L., Rodrigues Paulino, P. V. (Eds.), *Nutrient Requirements of Zebu Beef Cattle - BR - CORTE*. Federal University of Viçosa, Department of Animal Science, Viçosa; p. 185.
- Balsalobre, M. A. A., M. Corsi, P. M. Santos, I. Vieira, and R. R. Cárdenas. 2003. Nutritional quality of irrigated Tanzania grass under three post grazed stubbles intensities. *R. Bras. Zootec.* 32:519–528. doi:10.1590/S1516-35982003000300003 (in Portuguese).
- Beauchemin, K. A., M. Kreuzer, F. O'Mara, and T. A. McAllister. 2008. Nutritional management for enteric methane abatement: a review. *Aust. J. Exp. Agric.* 48:21–27. doi:10.1071/EA07199

- Beauchemin, K. A., and S. M. McGinn. 2006. Methane emissions from beef cattle: effects of fumaric acid, essential oil, and canola oil. *J. Anim. Sci.* **84**:1489–1496. doi:[10.2527/2006.8461489x](https://doi.org/10.2527/2006.8461489x)
- Benaouda, M., M. G. Ronquillo, L. T. Molina, and O. A. C. Ortega. 2017. Status of research on enteric methane emissions and mitigation strategies in Latin America. *Rev. Mex. Cienc. Agríc.* **8**:965–974. doi:[10.29312/remexca.v8i4.20](https://doi.org/10.29312/remexca.v8i4.20)
- Berndt, A., T. M. Boland, M. H. Deighton, J. I. Gere, C. Grainger, R. S. Hegarty, A. D. Iwaasa, J. P. Koolaard, K. R. Lassey, D. Luo, et al. 2014. *Guidelines for use of sulphur hexafluoride (SF₆) tracer technique to measure enteric methane emissions from ruminants*. Lambert, M. G. (Ed.), New Zealand: New Zealand Agricultural Greenhouse Gas Research Centre; p.166.
- Berndt, A., D. P. D. Lanna, G. M. da Cruz, R. R. Tullio, L. S. Sakamoto, and M. M. de Alencar. 2017. Prediction of the chemical body composition of Nellore and crossbreed bulls. *J. Anim. Sci.* **95**:3932–3939. doi:[10.2527/jas2017.1484](https://doi.org/10.2527/jas2017.1484)
- Berndt, A., and N. W. Tomkins. 2013. Measurement and mitigation of methane emissions from beef cattle in tropical grazing systems: a perspective from Australia and Brazil. *Animal* **7** (Suppl 2):363–372. doi:[10.1017/S1751731113000670](https://doi.org/10.1017/S1751731113000670)
- Boadi, D. A., K. M. Wittenberg, and A. D. Kennedy. 2002. Validation of the sulphur hexafluoride (SF₆) tracer gas technique for measurement of methane and carbon dioxide production by cattle. *Can. J. Anim. Sci.* **82**: 125–131. doi:[10.4141/A01-054](https://doi.org/10.4141/A01-054)
- Boddey, R. M., B. J. R. Alves, S. Urquiaga, C. P. Jantalia, L. Martin Neto, B. E. Madari, D. M. B. P. Milori, and P. L. O. A. Machado. 2012. Carbon stocks in soils in Brazil – quantity and mechanisms of accumulation and preservation. In: Lima, M. A., R. M. Boddey, B. J. R. Alves, P. L. O. A. Machado, and S. Urquiaga, editors. *Carbon stocks and greenhouse gas emissions in Brazilian agriculture*. Brasília (DF): Embrapa; p. 33–82 (in Portuguese).
- Buddle, B. M., M. Denis, G. T. Attwood, E. Altermann, P. H. Janssen, R. S. Ronimus, C. S. Pinares-Patiño, S. Muetzel, and D. Neil Wedlock. 2011. Strategies to reduce methane emissions from farmed ruminants grazing on pasture. *Vet. J.* **188**:11–17. doi:[10.1016/j.tvjl.2010.02.019](https://doi.org/10.1016/j.tvjl.2010.02.019)
- Canesin, R. C., T. T. Berchielli, J. D. Messana, F. Baldi, A. V. Pires, R. T. S. Frighetto, G. Fiorentini, and R. A. Reis. 2014. Effects of supplementation frequency on the ruminal fermentation and enteric methane production of beef cattle grazing in tropical pastures. *R. Bras. Zootec.* **43**:590–600. doi:[10.1590/S1516-35982014001100005](https://doi.org/10.1590/S1516-35982014001100005)
- Cardoso, A. S., A. Berndt, A. Leytem, B. J. R. Alves, I. N. O. Carvalho, L. H. B. Soares, S. Urquiaga, and R. M. Boddey. 2016. Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use. *Agric. Syst.* **143**:86–96. doi:[10.1016/j.agsy.2015.12.007](https://doi.org/10.1016/j.agsy.2015.12.007)
- Carvalho, I. P. C., G. Fiorentini, A. Berndt, P. S. Castagnino, J. D. Messana, R. T. S. Frighetto, R. A. Reis, and T. T. Berchielli. 2016. Performance and methane emissions of Nellore steers grazing tropical pasture supplemented with lipid sources. *R. Bras. Zootec.* **45**:760–767. doi:[10.1590/s1806-92902016001200005](https://doi.org/10.1590/s1806-92902016001200005)
- Castro, G. H. F., N. M. Rodriguez, L. C. Gonçalves, and R. M. Maurício. 2010. Productivity, agronomical and nutritional traits of Tanzânia grass cut on five different ages. *Arq. Bras. Med. Vet. Zootec.* **62**:654–666. doi:[10.1590/S0102-09352010000300022](https://doi.org/10.1590/S0102-09352010000300022) (in Portuguese).
- Clark, H., F. Kelliher, and C. Pinares-Patiño. 2011. Reducing CH₄ emissions from grazing ruminants in New Zealand: challenges and opportunities. *Asian-Australas. J. Anim. Sci.* **24**:295–302. doi:[10.5713/ajas.2011.r.04](https://doi.org/10.5713/ajas.2011.r.04)
- Costa, N. L., J. A. Magalhães, C. R. Townsend, and V. T. Paulino. 2004. *Physiology and management of forage plants*. Porto Velho: Embrapa Rondonia (Embrapa Rondonia. Documents); p. 85. 27: il. ISSN 0103-9865 (in Portuguese).
- Costa, J. A. A., and H. P. Queiroz. 2017. *Pasture management ruler*. rev. ed. Campo Grande (MS): Embrapa Beef Cattle (Embrapa Beef Cattle. Technical Report); p. 135. (in Portuguese).
- Dalchiavon, F. C., R. Montanari, and M. Andreotti. 2017. Production and quality of *Urochloa decumbens* (stapf) r.d.webster forage co-related to the physical and chemical properties of the soil. *R. Ceres.* **64**:315–326. doi:[10.1590/0034-737X201764030013](https://doi.org/10.1590/0034-737X201764030013)
- Demarchi, J. J. A. A., M. Q. Manella, O. Primavesi, R. T. S. Frighetto, L. A. Romero Solorzano, A. Berndt, and M. A. Lima. 2016. Effect of seasons on enteric methane emissions from cattle grazing *Urochloa brizantha*. *J. Agric. Sci.* **8**:1–10. doi:[10.5539/jas.v8n4p106](https://doi.org/10.5539/jas.v8n4p106)
- DeRamus, H. A., T. C. Clement, D. D. Giampola, and P. C. Dickison. 2003. Methane emissions of beef cattle on forages: efficiency of grazing management systems. *J. Environ. Qual.* **32**:269–277. doi:[10.2134/jeq2003.2690](https://doi.org/10.2134/jeq2003.2690)
- Dick, M., M. A. da Silva, and H. Dewes. 2015. Life cycle assessment of beef cattle production in two typical grassland systems of southern Brazil. *J. Clean. Prod.* **96**:426–434. doi:[10.1016/j.jclepro.2014.01.080](https://doi.org/10.1016/j.jclepro.2014.01.080)
- Eckard, R. J., C. Grainger, and C. A. M. de Klein. 2010. Options for the abatement of methane and nitrous oxide from ruminant production: a review. *Livest. Sci.* **130**:47–56. doi:[10.1016/j.livsci.2010.02.01](https://doi.org/10.1016/j.livsci.2010.02.01)
- FAO—Food and Agriculture Organization of the United Nations. 2013. *Tackling climate change through livestock. A global assessment of emissions and mitigation opportunities*. Rome (Italy): FAO; p. 115.
- FAO—Food and Agriculture Organization of the United Nations. 2017. *Livestock solutions for climate change*. Rome (Italy): FAO; p. 8. Available from <http://www.fao.org/3/I8098EN/i8098en.pdf>. [accessed August 24, 2020].
- Fiorentini, G., I. P. Carvalho, J. D. Messana, P. S. Castagnino, A. Berndt, R. C. Canesin, R. T. Frighetto, and T. T. Berchielli. 2014. Effect of lipid sources with different fatty acid profiles on the intake, performance, and methane emissions of feedlot Nellore steers. *J. Anim. Sci.* **92**:1613–1620. doi:[10.2527/jas.2013-6868](https://doi.org/10.2527/jas.2013-6868)
- Goering, H. K., and P. J. Van Soest. 1970. *Forage fiber analyses, apparatus, reagents, procedures and some applications (agricultural handbook, 279)*. Washington (DC): USDA.
- Grainger, C., T. Clarke, S. M. McGinn, M. J. Auld, K. A. Beauchemin, M. C. Hannah, G. C. Waghorn, H. Clark, and R. J. Eckard. 2007. Methane emissions from dairy cows measured using the sulfur hexafluoride (SF₆) tracer and chamber techniques. *J. Dairy Sci.* **90**:2755–2766. doi:[10.3168/jds.2006-697](https://doi.org/10.3168/jds.2006-697)
- Hammond, K. J., S. Muetzel, G. C. Waghorn, C. S. Pinares-Patino, J. L. Burke, and S. O. Hoskin. 2009. The variation in methane emissions from sheep and cattle is not explained by the chemical composition of ryegrass. *Proc. N. Z. Soc. Anim. Prod.* **69**:174–178.
- Herrero, M., B. Henderson, P. Havlik, P. K. Thornton, R. T. Conant, P. Smith, S. Wiersenius, A. N. Hristov, P. Gerber, M. Gill, et al. 2016. Greenhouse gas mitigation potentials in the livestock sector. *Nat. Clim. Change* **6**:452–461. doi:[10.1038/NCLIMATE2925](https://doi.org/10.1038/NCLIMATE2925)
- Hristov, A. N., J. Oh, J. L. Firkins, J. Dijkstra, E. Kebreab, G. Waghorn, H. P. Makkar, A. T. Adesogan, W. Yang, C. Lee, et al. 2013a. Special Topics—Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. *J. Anim. Sci.* **91**:5045–5069. doi:[10.2527/jas.2013-6583](https://doi.org/10.2527/jas.2013-6583)
- Hristov, A. N., J. Oh, J. L. Firkins, J. Dijkstra, E. Kebreab, G. Waghorn, H. P. Makkar, A. T. Adesogan, W. Yang, C. Lee, et al. 2013b. Special Topics—Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. *J. Anim. Sci.* **91**:5045–5069. doi:[10.2527/jas.2013-6583](https://doi.org/10.2527/jas.2013-6583)
- Johnson, K. A., and D. E. Johnson. 1995. Methane emissions from cattle. *J. Anim. Sci.* **73**:2483–2492. doi:[10.2527/1995.7382483x](https://doi.org/10.2527/1995.7382483x)

- Johnson, D. E., and G. M. Ward. 1996. Estimates of animal methane emissions. *Environ. Monit. Assess.* **42**:133–141. doi:[10.1007/BF00394046](https://doi.org/10.1007/BF00394046)
- Jonker, A., G. Molano, C. Antwi, and G. C. Waghorn. 2016. Enteric methane and carbon dioxide emissions measured using respiration chambers, the sulfur hexafluoride tracer technique, and a GreenFeed head-chamber system from beef heifers fed alfalfa silage at three allowances and four feeding frequencies. *J. Anim. Sci.* **94**:4326–4337. doi:[10.2527/jas.2016-0646](https://doi.org/10.2527/jas.2016-0646)
- Jose Neto, A., J. D. Messana, A. F. Ribeiro, E. S. Vito, L. G. Rossi, and T. T. Berchielli. 2015. Effect of starch-based supplementation level combined with oil on intake, performance, and methane emissions of growing Nellore bulls on pasture. *J. Anim. Sci.* **95**:2275–2284. doi:[10.2527/jas2014-8500](https://doi.org/10.2527/jas2014-8500)
- Koscheck, J. F. W., E. P. Romanzini, R. P. Barbero, L. M. Delevatti, A. C. Ferrari, J. T. Mulliniks, C. J. Mousquer, T. T. Berchielli, and R. A. Reis. 2020. How do animal performance and methane emission vary with forage management intensification and supplementation? *Anim. Prod. Sci.* **60**:1201–1209. doi:[10.1071/AN18712](https://doi.org/10.1071/AN18712)
- Martins, C. D. M., V. P. B. Euclides, R. A. Barbosa, D. B. Montagner, and T. Miqueloto. 2013. Forage intake and animal performance in *Urochloa humidicola* cultivars under continuous stocking. *Pesq. Agropec. Bras.* **48**:1402–1409. doi:[10.1590/S0100-204X2013001000012](https://doi.org/10.1590/S0100-204X2013001000012) (in Portuguese).
- Mauri, J., V. H. Techio, L. C. Davide, D. L. Pereira, F. S. Sobrinho, and F. J. Pereira. 2015. Forage quality in cultivars of *Brachiaria* spp.: association of lignin and fibers with anatomical characteristics. *Aust. J. Crop Sci.* **9**:1148–1153.
- Mazzetto, A. M., B. J. Feigl, R. L. M. Schils, C. E. P. Cerri, and C. C. Cerri. 2015. Improved pasture and herd management to reduce greenhouse gas emissions from a Brazilian beef production system. *Livest. Sci.* **175**:101–112. doi:[10.1016/j.livsci.2015.02.014](https://doi.org/10.1016/j.livsci.2015.02.014)
- McGinn, S. M., K. A. Beauchemin, A. D. Iwaasa, and T. A. McAllister. 2006. Assessment of the sulfur hexafluoride (SF₆) tracer technique for measuring enteric methane emissions from cattle. *J. Environ. Qual.* **35**:1686–1691. doi:[10.2134/jeq2006.0054](https://doi.org/10.2134/jeq2006.0054)
- MCTI. 2016. *Third National Communication of Brazil to the United Nations Framework Convention on Climate Change – Volume III/ Ministry of Science, Technology and Innovation*. Brasília: Ministério da Ciência, Tecnologia e Inovação; p. 333.
- Menezes, A. C. B., S. C. Valadares Filho, L. F. Costa e Silva, M. V. C. Pacheco, J. M. V. Pereira, P. P. Rotta, D. Zanetti, E. Detmann, F. A. S. Silva, L. A. Godoi, et al. 2016. Does a reduction in dietary crude protein content affect performance, nutrient requirements, nitrogen losses, and methane emission in finishing Nellore bulls? *Agr. Ecosyst. Environ.* **223**:239–249. doi:[10.1016/j.agee.2016.03.015](https://doi.org/10.1016/j.agee.2016.03.015)
- Mercadante, M. E. Z., A. P. M. Caliman, R. C. Canesin, S. F. M. Bonilha, A. Berndt, R. T. S. Frighetto, E. Magnani, and R. H. Branco. 2015. Relationship between residual feed intake and enteric methane emission in Nellore cattle. *R. Bras. Zootec.* **44**:255–262. doi:[10.1590/S1806-92902015000700004](https://doi.org/10.1590/S1806-92902015000700004)
- Moore, J. E., and G. O. Mott. 1974. Recovery of residual organic matter from in vitro digestion of forages. *J. Dairy Sci.* **57**:1258–1259. doi:[10.3168/jds.S0022-0302\(74\)85048-4](https://doi.org/10.3168/jds.S0022-0302(74)85048-4)
- Moraes, L. E., A. B. Strathe, J. G. Fadel, D. P. Casper, and E. Kebreab. 2014. Prediction of enteric methane emissions from cattle. *Glob. Chang. Biol.* **20**:2140–2148. doi:[10.1111/gcb.12471](https://doi.org/10.1111/gcb.12471)
- Mott, G. O., and H. L. Lucas. 1952. The design, conduct and interpretation of grazing trials on cultivated and improved pastures. In: *Proceedings of the 6th International Grassland Congress*. Pennsylvania State College, Pennsylvania; p. 1380–1395.
- Nascimento, C. F. M., A. Berndt, L. A. Romero Solorzano, P. M. Meyer, R. T. S. Frighetto, J. J. A. A. Demarchi, and P. H. M. Rodrigues. 2016. Methane emission of cattle fed *Urochloa brizantha* hay harvested at different stages. *J. Agric. Sci.* **8**:163–174. doi:[10.5539/jas.v8n1p163](https://doi.org/10.5539/jas.v8n1p163)
- Oliveira, P. P. A. 2015. Greenhouse gases in Brazilian livestock production systems and the importance of the carbon balance for environmental preservation. *R. Bras. Geo. Física* **8**:623–634. doi:[10.5935/1984-2295.20150019](https://doi.org/10.5935/1984-2295.20150019) (in Portuguese).
- Oliveira, P. P. A., R. R. S. Corte, S. L. Silva, P. H. M. Rodriguez, L. S. Sakamoto, A. F. Pedroso, R. R. Tullio, and A. Berndt. 2018. The effect of grazing system intensification on the growth and meat quality of beef cattle in the Brazilian Atlantic Forest biome. *Meat Sci.* **139**:157–161. doi:[10.1016/j.meatsci.2018.01.019](https://doi.org/10.1016/j.meatsci.2018.01.019)
- Oliveira, P. P. A., A. C. Primavesi, A. C. Camargo, W. M. Ribeiro, and E. T. M. Silva. 2005. *Recommendation of forage oat overgrazing in irrigated tropical or subtropical pastures*. São Carlos (SP): Embrapa Southeast Livestock (Embrapa Southeast Livestock. Technical Report); p. 61:1–7 (in Portuguese).
- Oliveira Silva, R., L. G. Barioni, J. A. J. Hall, M. F. Matsuura, T. Z. Albertini, F. A. Fernandes, and D. Moran. 2016. Increasing beef production could lower greenhouse gas emissions in Brazil if decoupled from deforestation. *Nat. Clim. Change* **6**:493–497. doi:[10.1038/NCLIMATE2916](https://doi.org/10.1038/NCLIMATE2916)
- Oliveira Silva, R., L. G. Barioni, J. A. J. Hall, A. C. Moretti, R. F. Veloso, P. Alexander, M. Crespolini, and D. Moran. 2017. Sustainable intensification of Brazilian livestock production through optimized pasture restoration. *Agric. Syst.* **153**:201–211. doi:[10.1016/j.agsy.2017.02.001](https://doi.org/10.1016/j.agsy.2017.02.001)
- Owens, F. N., P. Dubeski, and C. F. Hanson. 1993. Factors that alter the growth and development of ruminants. *J. Anim. Sci.* **71**:3138–3150. doi:[10.2527/1993.71113138x](https://doi.org/10.2527/1993.71113138x)
- Paciullo, D. S. C., C. A. M. Gomide, C. R. T. Castro, R. M. Maurício, P. B. Fernandes, and M. J. F. Morenz. 2016. Morphogenesis, biomass and nutritive value of *Panicum maximum* under different shade levels and fertilizer nitrogen rates. *Grass Forage Sci.* **72**:590–600. doi:[10.1111/gfs.12264](https://doi.org/10.1111/gfs.12264)
- Paciullo, D. S. C., J. A. Gomide, D. S. Queiroz, and E. A. M. da Silva. 2001. Chemical composition and in vitro digestibility of leaf blades and stems of forages grasses, according to level of insertion on grass tiller, age and season of growth. *Rev. Bras. Zootec.* **30**:964–974. doi:[10.1590/S1516-35982001000400009](https://doi.org/10.1590/S1516-35982001000400009) (in Portuguese).
- Palieraqui, J. G. B., C. A. A. Fontes, E. G. Ribeiro, A. C. Cóser, C. E. Martins, and A. M. Fernandes. 2006. Influence of irrigation on the availability, chemical composition, digestibility and intake of mombaça grass and napier grass. *R. Bras. Zootec.* **35**:2381–2387. doi:[10.1590/S1516-35982006000800026](https://doi.org/10.1590/S1516-35982006000800026) (in Portuguese).
- Patra, A. K. 2012. Enteric methane mitigation technologies for ruminant livestock: a synthesis of current research and future directions. *Environ. Monit. Assess.* **184**:1929–1952. doi:[10.1007/s10661-011-2090-y](https://doi.org/10.1007/s10661-011-2090-y)
- Pereira, L. G. R., F. S. Machado, M. M. Campos, R. Guimaraes Júnior, T. R. Tomich, L. G. Reis, and C. Coombs. 2015. Enteric methane mitigation strategies in ruminants: a review. *Rev. Colomb. Cienc. Pecu.* **28**:124–143. doi:[10.17533/udea.rccp.v28n2a02](https://doi.org/10.17533/udea.rccp.v28n2a02)
- Pinares-Patiño, C.S., and H. Clark. 2008. Reliability of the sulfur hexafluoride tracer technique for methane emission measurement from individual animals: an overview. *Aust. J. Exp. Agr.* **48**:223–229. doi:[10.1071/EA07297](https://doi.org/10.1071/EA07297)
- Pontes, L. da S., R. S. Barro, J. V. Savian, A. Berndt, J. L. Moletta, V. Porfírio da Silva, C. Bayer, and P. C. de F. Carvalho. 2018. Performance and methane emissions by beef heifer grazing in temperate pastures and in integrated crop-livestock systems: the effect of shade and nitrogen fertilization. *Agric. Ecosyst. Environ.* **253**:90–97. doi:[10.1016/j.agee.2017.11.009](https://doi.org/10.1016/j.agee.2017.11.009)
- Ribeiro, E. G., C. A. A. Fontes, M. L. P. Lima, C. E. Martins, A. C. Cóser, and E. E. L. Barros. 2010. Nutritive value of Elephant grass and Mombasa grass under irrigation influence and sequential grazing day. *B. Indústria Anim.* **67**:115–124 (in Portuguese).
- Ribeiro, E. G., C. A. A. Fontes, J. G. B. Palieraqui, C. E. Martins, A. C. Cóser, and N. F. Sant'Ana. 2008. Effect of irrigation, during dry and rainy season, on stocking rate, intake and

- performance of steers grazing “Mombasa” guinea grass and “Napier” elephant grass. *R. Bras. Zootec.* **37**:1546–1554. doi:[10.1590/S1516-35982008000900005](https://doi.org/10.1590/S1516-35982008000900005) (in Portuguese).
- Richmond, A. S., A. R. Wylie, A. S. Laidlaw, and F. O. Lively. 2015. Methane emissions from beef cattle grazing on semi-natural upland and improved lowland grasslands. *Animal* **9**:130–137. doi:[10.1017/S1751731114002067](https://doi.org/10.1017/S1751731114002067)
- Rossi, L. G., G. Fiorentini, B. R. Vieira, A. José Neto, J. D. Messana, E. B. Malheiros, and T. T. Berchielli. 2017. Effect of ground soybean and starch on intake, digestibility, performance, and methane production of Nellore bulls. *Anim. Feed Sci. Tech.* **226**:39–47. doi:[10.1016/j.anifeedsci.2017.02.004](https://doi.org/10.1016/j.anifeedsci.2017.02.004)
- Sakamoto, L. S., M. E. Mercadante, S. F. Bonilha, R. H. Branco, E. F. Bonilha, and E. Magnani. 2014. Prediction of retail beef yield and fat content from live animal and carcass measurements in Nellore cattle. *J. Anim. Sci.* **92**:5230–5238. doi:[10.2527/jas.2012-6065](https://doi.org/10.2527/jas.2012-6065)
- Salman, A. K. D., J. P. G. Soares, and R. C. Canesin. 2006. *Sampling methods for quantitative pasture assessment*. vol. **84**. Porto Velho: Embrapa Rondônia – Circular Técnica; p. 1–6 (in Portuguese).
- Santos, L. C., P. Bonomo, C. C. F. Silva, A. J. V. Pires, C. M. Veloso, and N. M. S. Patês. 2008. Production and chemical composition of *Brachiaria brizantha* and *Brachiaria decumbens* submitted to different fertilization. *Ciênc. Anim. Bras.* **9**:856–866 (in Portuguese). doi:[10.5216/cab.v9i4.1118](https://doi.org/10.5216/cab.v9i4.1118)
- Savian, J. V., A. Barth Neto, D. B. David, C. Bremm, R. M. T. Schons, T. C. M. Genro, G. A. Amaral, J. Gere, C. M. McManus, C. Bayer, et al. 2014. Grazing intensity and stocking methods on animal production and methane emission by grazing sheep: implications for integrated crop–livestock system. *Agric. Ecosyst. Environ.* **190**:112–119. doi:[10.1016/j.agee.2014.02.008](https://doi.org/10.1016/j.agee.2014.02.008)
- Segnini, A., A. A. P. Xavier, P. L. Otaviani Junior, P. P. A. Oliveira, A. de F. Pedroso, M. F. F. M. Praes, P. H. M. Rodrigues, and D. M. B. P. Milori. 2019. Soil carbon stock and humification in pastures under different levels of intensification in Brazil. *Sci. Agric.* **76**:33–40. doi:[10.1590/1678-992X-2017-0131](https://doi.org/10.1590/1678-992X-2017-0131)
- Simili, F. F., N. C. Lima, M. L. P. Lima, A. L. dos Santos, P. R. Leme, and T. T. Berchielli. 2007. Degradability of Elephant grass Guaçu and Tanzania Guinea grass sampled as extrusa and hand-plucked. *B. Indústria Anim.* **64**:311–319 (in Portuguese).
- Smith, P. 2014. Do grasslands act as a perpetual sink for carbon? *Glob. Chang. Biol.* **20**:2708–2711. doi:[10.1111/gcb.12561](https://doi.org/10.1111/gcb.12561)
- Sousa, R. S., A. J. V. Pires, G. G. P. Carvalho, F. F. Silva, A. F. Magalhães, and C. M. Veloso. 2010. Chemical composition of Tanzania grass fertilized with nitrogen and phosphorus. *R. Bras. Zootec.* **39**:1200–1205. doi:[10.1590/S1516-35982010000600006](https://doi.org/10.1590/S1516-35982010000600006) (in Portuguese).
- Soussana, J. F., and G. Lemaire. 2014. Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop–livestock systems. *Agric. Ecosyst. Environ.* **190**:9–17. doi:[10.1016/j.agee.2013.10.012](https://doi.org/10.1016/j.agee.2013.10.012)
- Veloso, A. L. C. 2012. *Irrigated pasture of Panicum maximum Jacq cv Tanzania fertilized with phosphorus and nitrogen on yield, nutritive value and soil attributes in northern Minas Gerais [PhD thesis]*. Belo Horizonte (Brazil): Universidade Federal de Minas Gerais (in Portuguese).
- Wang, L. A., and Z. Goonewardene. 2004. The use of MIXED models in the analysis of animal experiments with repeated measures data. *Can. J. Anim. Sci.* **84**:1–11. doi:[10.4141/A03-123](https://doi.org/10.4141/A03-123)
- Warner, D., A. Bannink, B. Hatew, H. van Laar, and J. Dijkstra. 2017. Effects of grass silage quality and level of feed intake on enteric methane production in lactating dairy cows. *J. Anim. Sci.* **95**:3687–3700. doi:[10.2527/jas.2017.1459](https://doi.org/10.2527/jas.2017.1459)
- Warner, D., B. Hatew, S. C. Podesta, G. Klop, S. van Gastelen, H. van Laar, J. Dijkstra, and A. Bannink. 2016. Effects of nitrogen fertilization rate and maturity of grass silage on methane emission by lactating dairy cows. *Animal* **10**:34–43. doi:[10.1017/S1751731115001640](https://doi.org/10.1017/S1751731115001640)