



Relationship between residual feed intake and enteric methane emission in Nellore cattle

Maria Eugênia Zerlotti Mercadante¹, Ana Paula de Melo Caliman¹, Roberta Carrilho Canesin¹, Sarah Figueiredo Martins Bonilha¹, Alexandre Berndt², Rosa Toyoko Shiraishi Frighetto³, Elaine Magnani¹, Renata Helena Branco¹

¹ Instituto de Zootecnia, Centro Avançado de Pesquisa Tecnológica do Agronegócio de Bovinos de Corte, Sertãozinho, SP, Brasil.

² Embrapa Pecuária Sudeste, São Carlos, SP, Brasil.

³ Embrapa Meio Ambiente, Jaguariúna, SP, Brasil.

ABSTRACT - Feed intake and average daily gain (ADG) in Nellore cattle were determined to calculate residual feed intake in two performance tests: first during the growth phase (RFI_{growth}) and then during a measurement of the methane emission phase (RFI_{met}). During the RFI_{growth} test, 62 males and 56 females were classified as low-, medium-, and high- RFI . Enteric methane emission was measured in 46 animals; 23 males used for RFI_{met} measurement plus 23 females (22 low- RFI_{growth} and 24 high- RFI_{growth}). Diet consisted of *Brachiaria brizantha* cv. Marandu hay (445 g/kg DM) and concentrate (555 g/kg DM). During the RFI_{growth} and RFI_{met} phases, DMI was lower in the animals with low RFI , with no difference in ADG. Residual feed intake was -0.359 and 0.367 kg DM/d for low- and high- RFI animals. Enteric methane emission (g/d, g/kg $BW^{0.75}$ and g/kg ADG) did not differ between RFI_{growth} classes. Enteric methane emission (g/d) was higher in high RFI_{met} and lower in low RFI_{met} males. Spearman correlations among traits obtained during both tests, which were high between metabolic BW ($r = 0.959$) and between DMI ($r = 0.718$), and zero between ADG ($r = -0.062$), resulted in moderate correlation between RFI_{growth} and RFI_{met} ($r = 0.412$). However, it is not possible to confirm that high-efficiency animals release less enteric methane, since different results were obtained when enteric methane was compared between the RFI_{growth} and RFI_{met} classes.

Key Words: beef cattle, enteric methane production, feed efficiency, performance, sulfur hexafluoride

Introduction

Residual feed intake (RFI) is an attractive measure of feed efficiency, as it does not depend on body size, growth rate, or body composition measures (Durunna et al., 2012). High-efficiency animals exhibit low RFI and consume less feed than expected for maintenance and production, whereas low-efficiency animals have high RFI and observed feed intake higher than the predicted feed intake.

The possibility of improving production efficiency by exploiting the genetic variation in RFI and possible variation in traits related to emission of greenhouse gases is of great economic importance for beef cattle production. Studies have shown that selection of animals for low RFI (high feed efficiency) reduces methane emissions in cattle (Nkrumah et al., 2006; Hegarty et al., 2007; Fitzsimons et al., 2013). However, there are inconsistencies in relation to differences in feed intake and corresponding methane

emissions between low- and high- RFI animals. Fitzsimons et al. (2013) offered grass silage to heifers and observed that both DMI and methane emission (g/d) were lower for low- RFI compared with high- RFI animals, and Jones et al. (2011) reported that DMI was similar between divergent RFI groups and that methane emission was similar when animals grazed low-quality pastures but were lower for low- RFI compared with high- RFI animals when grazing high-quality pastures. The conflicting observations regarding the variation in methane emission of high- and low-efficiency animals between studies suggest that selection of cattle for increasing feed efficiency does not necessarily result in a reduction in methane emission (Freetly and Brown-Brandl, 2013). To date, published studies relating RFI and methane emission are limited to *Bos taurus* cattle, and little information is available on *Bos indicus* cattle.

In view of these considerations, the objective of the present study was to evaluate the relationship between enteric methane emission and residual feed intake in Nellore cattle fed a high-roughage diet.

Material and Methods

The experiment was approved by the Animal Ethics Committee of Instituto de Zootecnia, Nova Odessa, Brazil,

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Corresponding author: mercadante@iz.sp.gov.br

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in accordance with Guidelines of Animal Welfare and Humane Slaughter (São Paulo State law number 11.977).

The study was conducted in Sertãozinho, northern region of the state of São Paulo, Brazil (21°10' South latitude and 48°5' West longitude). The climate of the region is tropical humid, with average annual temperature and rainfall of 24 °C and 1,312 mm, respectively.

For RFI identification, Nellore cattle born in 2010 were evaluated in individual performance tests, in an incomplete block design. One hundred eighteen animals, consisting of 62 males (starting at 261±23.1 d of age and 243±40.1 kg of BW) and 56 females (starting at 290±26.3 d of age and 216±30.8 kg BW), were evaluated for RFI_{growth} to identify high- (low RFI), intermediate- (medium RFI) and low-efficiency (high RFI) animals. After RFI_{growth} identification, enteric methane emission measurement was performed in 46 animals (23 males and 23 females). Next, in order to obtain an estimate of individual feed intake and RFI at the time of enteric methane emission measurement, a new RFI (RFI_{met}) was calculated, but only in males (n = 23; starting at 351 d of age and 343 kg BW).

Animals were fed twice a day (08.00 h and 15.00 h), with *ad libitum* access to feed and water. The diet consisted of *Brachiaria brizantha* cv. Marandu hay (445 g/kg dry matter, DM), ground corn (322 g/kg DM), cottonseed meal (214 g/kg DM), urea (4.5 g/kg DM), and mineral salt (14.5 g/kg DM) (Table 1), for 0.800 kg/d of ADG (NRC, 2000).

Animals were housed in individual pens: one facility destined for males and two other facilities for females to fit the number of evaluated animals. Voluntary feed intake was calculated as the difference between feed supplied and refusals. The amount of feed offered was adjusted daily based on the intake observed on the previous day to

maintain refusals at about 10% of the feed supplied. Diet samples were collected at intervals of 28 d and the refusals per animal were weighed daily and sampled twice a week. The samples were stored in properly labeled plastic bags and frozen.

Samples of feed and refusals were oven-dried at 55 °C for 72 h and ground through a 1-mm screen (Wiley mill, Arthur Hill Thomas Co., Philadelphia, PA). These samples were analyzed for nitrogen (N) (AOAC Official Method 984.13), ash (AOAC Official Method 942.05), and EE (AOAC Official Method 920.39) contents, in accordance with the AOAC (1990). Neutral (NDF) and acid (ADFom) detergent fiber analyses were based on procedures described by Mertens (2002). Lignin (sa) was estimated as described by Van Soest and Robertson (1985). Gross energy was determined using an adiabatic bomb calorimeter (model 6300, Parr Instrument Company, Moline, IL, USA).

Two performance tests (males and females) were conducted to calculate RFI_{growth}. For males, the performance test lasted 107 d, whereas for females it lasted 112 d (Figure 1). The adaptation periods were 35 and 28 d for males and females, respectively, and these data were not included in the RFI_{growth} period. Therefore, serial BW and individual feed intake data were obtained for 72 (July 5 to September 14, 2011) and 83 d (August 3 to October 25, 2011) for males and females, respectively. The males' ADG was determined based on two records per week on consecutive days at intervals of 14 d without fasting (total of 22 weight records). For females, individual BW records were obtained at intervals of 28 d, with deprivation of water and feed for 16 h (total of four weight records).

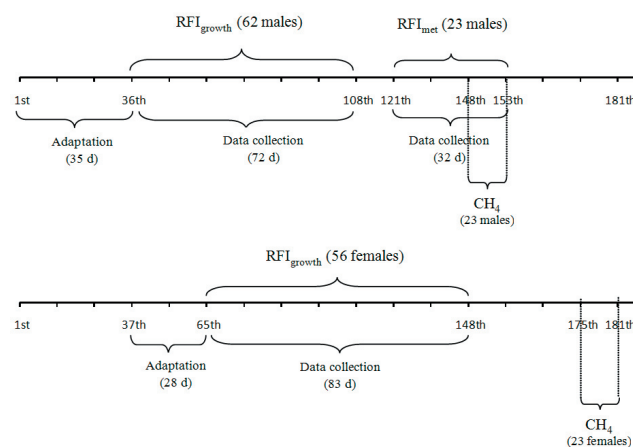
Table 1 - Nutrient composition of the ingredients and total diet offered to the animals during the period of evaluation of residual feed intake

Nutrient	Ingredient			Total diet
	Hay	Corn	Cottonseed meal	
Dry matter, g/kg (as fed)	948	959	958	934
Ash ¹	19.0	51.5	57.3	37.4
Crude protein ¹	27.6	94.3	327	113
Ether extract ¹	30.0	45.0	28.0	28.4
Neutral detergent fiber ¹	789	142	473	500
Acid detergent fiber ¹	491	40.6	335	310
Cellulose ¹	391	33.2	217	239
Lignin (sa) ¹	69.6	10.5	119	61.8
Gross energy, Mcal/kg	4.02	4.30	4.31	4.09
Total digestible nutrients,% ²	-	-	-	70.5
Metabolizable energy, kcal/kg ³	-	-	-	2.55

¹ Expressed as percentage of dry matter (g/kg DM).

² Values calculated by Weiss' equation (Weiss, 1999).

³ Values calculated by NRC (2000) level 2.



RFI_{growth} - residual feed intake in the growth phase; RFI_{met} - residual feed intake in the methane emission phase.

Figure 1 - Chronological plan for RFI_{growth} (males and females), RFI_{met} (males), and measurement of enteric CH₄ (males and females) in the experimental period.

After the RFI_{growth} period, 23 males were sampled for RFI_{met} analysis — 11 lowest RFI_{growth} and 12 highest RFI_{growth} . These animals continued for an additional 45 d in individual pens (including the period of methane collection) with daily records of DMI. However, to meet the herd selection criteria (Mercadante et al., 2003), one fasting weighing was performed on d 9, causing the first 13 d to be invalidated. Therefore, the performance test was conducted over the last 32 d (September 27 to October 30, 2011) (Figure 1). Average daily gain was determined based on nine weighing records of animals without previous fasting, which allowed for the calculation of a new RFI (RFI_{met}), more representative of the methane-emission measurement period. This was done despite the fact that at least 63 d of evaluation are necessary to obtain accurate estimates of ADG (Wang et al., 2006).

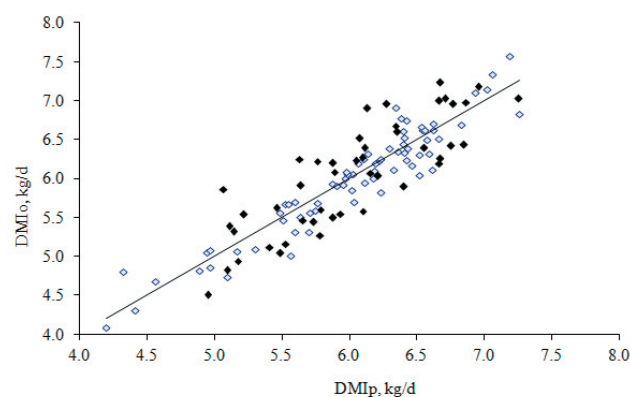
Enteric methane emission (g/d) was measured in 46 animals (Figure 2) — 22 low- RFI_{growth} animals (11 males and 11 females) and 24 high- RFI_{growth} animals (12 males and 12 females). Data were collected for six consecutive days over a period of 24 h, from the 148th to the 153th day for males (October 25 to October 30, 2011) and from the 175th to the 181th day for females (November 21 to November 27, 2011) (Figure 1), using the sulfur hexafluoride (SF_6) tracer gas technique as described by Johnson and Johnson (1995), adapted by Primavesi et al. (2004). The permeation tubes were filled with approximately 1.0 g SF_6 . To confirm the emission rate of SF_6 , the permeation tubes were kept in a water bath at 39 °C and weighed eight times to construct an 8-point regression curve. The tubes were administered orally to each animal in a random manner 4 d before the beginning of methane sampling.

Expired and eructated gases, together with ambient air, were sampled in 60-mm class 20 polyvinyl chloride (PVC) canisters through a stainless steel capillary tube (inner diameter: 0.127 mm) fixed to the halter of the animals. The sampling canisters were evacuated before placement into the animals and gases were analyzed about 5 d after sample collection, as the experiment was conducted far from the laboratory of gas analysis.

To correct atmospheric concentrations of methane inside the facility, gas samples were collected from ambient air with two sampling canisters per day (“blank”), hung at the entrance and exit of the facility. At the end of the sampling period, SF_6 and CH_4 concentrations in the samples were determined by gas chromatography using an HP6890 gas chromatograph equipped with a flame ionization detector (FID) and Plot HP-AI/M megabore column (0.53 μm , 30 m) for CH_4 , and with an electron capture detector (μ -ECD) and HP-MolSiv megabore column for SF_6 , using two 0.5-cm³

loops coupled to two 6-way valves. The canisters were pressurized with nitrogen 5.0 (White Martins, Praxair Inc) until reaching a pressure of approximately 1.2 atm. Pressure readings were obtained with a digital pressure meter. The calibration curves were constructed, using gas standards certified by White Martins (Praxair Inc), as described by Westberg et al. (1998). The flow rate of CH_4 released by the animal was calculated in relation to the flow of SF_6 , correlating the results with the known release rate of SF_6 in the rumen, subtracted from baseline CH_4 concentrations (Westberg et al., 1998): $Q_{CH_4} = Q_{SF_6} \times ([CH_4]_Y - [CH_4]_B) / [SF_6]$, in which Q_{CH_4} = emission rate of CH_4 by the animal; Q_{SF_6} = known release rate of SF_6 ; $[CH_4]_Y$ = concentration of CH_4 in the canister; $[CH_4]_B$ = concentration of CH_4 in the blank; and $[SF_6]$ = concentration of sulfur hexafluoride in the canister. The equation of Blaxter and Clapperton (1965), corrected by Wilkerson et al. (1995), was used to calculate the loss of gross energy in the form of methane: $CH_4/GEI = [(CH_4 \times 0.0133)/GEI] \times 100$, in which GEI is the gross energy intake and 0.0133 is the gross energy in Mcal/g CH_4 (Holter and Young, 1992).

Residual feed intake was calculated as the difference between observed DMI and DMI predicted by regressing DMI on ADG and average $BW^{0.75}$ (Koch et al., 1963). The dry matter intake was calculated based on the mean of feed intake values obtained during each test period (RFI_{growth} and RFI_{met}) multiplied by the dry matter concentration of the diet. The average daily gain in each test was estimated as the linear regression coefficient of BW on j days of test: $y_i = \alpha + \beta \times \text{Dot}_i + \varepsilon_i$, in which y_i = BW in the i -th observation; α = intercept of the regression equation corresponding to the initial BW ; β = linear regression coefficient corresponding



Open symbols represent all animals tested for residual feed intake during the growth phase (RFI_{growth} , $n = 118$) and black solid symbols represent animals used for measurement of enteric methane emission ($n = 46$).

Figure 2 - Relationship between observed (DMIo) and predicted (DMIp) dry matter intake.

to ADG; Dot_i = days of test for the i -th observation; and ϵ_i = random error associated with each observation. The mean $\text{BW}^{0.75}$ during the test was calculated as: $\text{BW}^{0.75} = [\alpha + \beta \times (\text{Dot} / 2)]^{0.75}$, with α and β assuming the values obtained by the equation described above (Grion et al., 2014).

Residual feed intake was estimated using the following regression equation: $\text{DMI} = \beta_T \times \text{TG} + \beta_{\text{TA}} \times \text{TG} \times \text{ADG} + \beta_{\text{TB}} \times \text{TG} \times \text{BW}^{0.75} + \epsilon$ (i.e., RFI), in which β_T , β_{TA} , and β_{TB} are regression coefficients of the classificatory variable test group (TG) and of the interactions between TG and the covariates ADG and $\text{BW}^{0.75}$, respectively; and ϵ is the residual of the equation (i.e., RFI). TG is the test group [sex and two facilities only for females, TG = 1 (male, n = 62), 2 (female, n = 31), and 3 (female, n = 25)]. Animals were classified into three groups: low $\text{RFI}_{\text{growth}}$ (<mean - 0.5 SD; n = 40); medium $\text{RFI}_{\text{growth}}$ (± 0.5 SD of the mean; n = 42), and high $\text{RFI}_{\text{growth}}$ (>mean + 0.5 SD; n = 36), taking into consideration the standard deviation (SD) of the mean RFI (SD = 0.309 kg DMI for males and SD = 0.329 kg DMI for females). For RFI_{met} , males were classified as low-RFI (<zero) and high-RFI (>zero), considering that the mean RFI is zero.

Variables were compared between two RFI classes (low and high) by the least square method. The statistical model included the effects of $\text{RFI}_{\text{growth}}$ class (low or high RFI) and sex (male or female), or the effect of RFI_{met} class. The interaction between $\text{RFI}_{\text{growth}}$ class and sex was not significant for the analyzed variables and was therefore removed from the model. Spearman correlations were computed to compare ADG, DMI, $\text{BW}^{0.75}$, and RFI across the two test periods for the male calves.

Results

No significant differences in initial BW, final BW, $\text{BW}^{0.75}$, or ADG were observed between low- and high- $\text{RFI}_{\text{growth}}$ animals (Table 2). $\text{RFI}_{\text{growth}}$ was -0.359 and 0.367 kg DM/d for low- and high- $\text{RFI}_{\text{growth}}$ animals, respectively, corresponding to a difference of 0.720 kg/d in DMI between high and low-efficiency animals. Animals classified as high- $\text{RFI}_{\text{growth}}$ consumed 11% more than low- $\text{RFI}_{\text{growth}}$ animals. Enteric methane emission (g/d and g/kg $\text{BW}^{0.75}$) did not differ when compared between $\text{RFI}_{\text{growth}}$ classes ($P > 0.05$). On the other hand, methane emission expressed as g/kg DMI was higher in low- $\text{RFI}_{\text{growth}}$ animals ($P < 0.001$). No effect on enteric methane emission was found in $\text{RFI}_{\text{growth}}$ when expressed as g/kg ADG ($P = 0.304$) (Table 2).

After the RFI_{met} test period (32 d), males were re-ranked as low- and high- RFI_{met} (n = 23). The animals did not differ in terms of $\text{BW}^{0.75}$ or ADG ($P > 0.05$) between RFI_{met} classes. However, DMI was higher in bulls classified as high- RFI_{met}

(8.12 \pm 0.14 kg/d) compared with the low- RFI_{met} (7.09 \pm 0.17 kg/d). The same was observed for gross energy intake (GEI), which was 33.5 \pm 0.55 Mcal/d and 29.5 \pm 0.69 Mcal/d for high- and low- RFI_{met} animals, respectively. Results of -0.506 and 0.362 kg DM/d were found for animals with low and high RFI_{met} , respectively, with a variation of 0.868 kg/d in DMI between high and low-efficiency animals, corresponding to a 13% higher intake in high RFI_{met} animals (Table 3). When methane emission (g/d) was compared between RFI_{met} classes, it was higher for high RFI_{met} than low RFI_{met} animals ($P < 0.05$). Methane emission (g/kg DMI and %GEI) did not differ between RFI_{met} classes ($P > 0.05$).

A positive correlation was observed for $\text{BW}^{0.75}$ ($r = 0.959$) and DMI ($r = 0.718$) between $\text{RFI}_{\text{growth}}$ and RFI_{met} , even considering the short duration of the RFI_{met} test (32 d).

Table 2 - Performance traits, enteric methane emission, and feed efficiency of Nellore males and females classified as low- and high-residual feed intake ($\text{RFI}_{\text{growth}}$)

Trait	$\text{RFI}_{\text{growth}}$		P-value
	Low (n = 22)	High (n = 24)	
Initial BW, kg	238 \pm 6.83	236 \pm 6.54	0.795
Final BW, kg	297 \pm 7.01	293 \pm 6.72	0.693
$\text{BW}^{0.75}$, kg	66.1 \pm 1.26	65.0 \pm 1.26	0.781
DMI, kg/d	5.66 \pm 0.120	6.38 \pm 0.120	<0.001
ADG, kg/d	0.754 \pm 0.020	0.744 \pm 0.020	0.810
RFI, kg DM/d	-0.359 \pm 0.040	0.367 \pm 0.030	<0.001
Enteric methane emission			
CH_4 , g/d	142 \pm 3.81	144 \pm 3.64	0.691
CH_4 , g/kg $\text{BW}^{0.75}$	2.16 \pm 0.056	2.21 \pm 0.054	0.500
CH_4 , g/kg DMI	25.1 \pm 0.588	22.8 \pm 0.563	<0.001
CH_4 , g/kg ADG	191 \pm 7.99	203 \pm 7.65	0.304

BW - body weight; $\text{BW}^{0.75}$ - metabolic body weight; DMI - dry matter intake; ADG - average daily gain; RFI - residual feed intake.

Table 3 - Performance traits, enteric methane emission, and feed efficiency of young Nellore males classified as low- and high-residual feed intake (RFI_{met})

Trait	RFI_{met}		P-value
	Low (n = 9)	High (n = 14)	
Initial BW, kg	326 \pm 11.4	332 \pm 9.60	0.699
Final BW, kg	351 \pm 10.8	358 \pm 9.13	0.613
$\text{BW}^{0.75}$, kg	78.9 \pm 1.90	80.2 \pm 1.60	0.611
DMI, kg/d	7.09 \pm 0.163	8.12 \pm 0.140	<0.001
GEI, Mcal/d	29.5 \pm 0.690	33.5 \pm 0.550	<0.001
ADG, kg/d	0.467 \pm 0.170	0.547 \pm 0.150	0.726
RFI, kg DM/d	-0.506 \pm 0.076	0.362 \pm 0.064	<0.001
Enteric methane emission ¹			
CH_4 , g/d	144 \pm 6.08	163 \pm 4.87	0.024
CH_4 , g/kg $\text{BW}^{0.75}$	2.69 \pm 0.087	2.37 \pm 0.700	0.013
CH_4 , g/kg DMI	24.4 \pm 1.10	25.7 \pm 0.879	0.381
CH_4 , % GEI	6.49 \pm 0.200	6.46 \pm 0.160	0.937
CH_4 , g/kg ADG	186 \pm 10.7	191 \pm 8.57	0.689

BW - body weight; $\text{BW}^{0.75}$ - metabolic body weight; DMI - dry matter intake; GEI - gross energy intake; ADG - average daily gain; RFI - residual feed intake.

¹ Same records were shown in Table 2, excluding females.

However, a correlation close to zero was observed for ADG ($r = -0.062$) between test periods. Spearman correlation showed a positive association between RFI_{growth} and RFI_{met} ($r = 0.412$) (Table 4), with strong evidence of animal re-ranking between RFI_{growth} and RFI_{met} .

Table 4 - Spearman correlation coefficients between performance traits and residual feed intake (RFI) of Nellore cattle obtained during the two evaluation periods of RFI (RFI_{growth} and RFI_{met})

	Trait _{met}
$BW^{0.75}_{\text{growth}}$	0.959***
DMI_{growth}	0.718***
ADG_{growth}	-0.062 ns
RFI_{growth}	0.412*

BW - body weight; DMI - dry matter intake; ADG - average daily gain; $BW^{0.75}$ - metabolic body weight; ns - not significant.

* $P < 0.05$; *** $P < 0.0001$.

Discussion

No differences in ADG were observed between RFI_{growth} classes (Table 2), despite a difference in DMI between low- and high- RFI_{growth} animals ($P > 0.001$) due to the definition of RFI itself (Koch et al., 1963). This fact has also been reported in recent studies demonstrating that RFI is independent of ADG in cattle (Fitzsimons et al., 2013; Durunna et al., 2012; Lawrence et al., 2012; Cruz et al., 2010). The ADG of animals classified as low- and high- RFI_{growth} (0.754 vs 0.744 kg/d, $P = 0.810$) during the RFI_{growth} test was moderate and is consistent with that observed for weaned Nellore animals fed *Brachiaria brizantha* hay-based diet and concentrate. Similar ADG values (0.820 kg/d) were reported by Sobrinho et al. (2011) for Nellore bulls selected for post-weaning weight that received a similar diet. On the other hand, ADG was numerically lower in the animals classified as low- and high- RFI_{met} (0.466 and 0.547 kg/d, respectively; $P = 0.726$) during the RFI_{met} test when the animals received the same diet. Even though the diet and facility were the same and the DMI expressed as percentage of average test BW (2.2%) were similar in growth and methane phases, lower ADG was observed during RFI_{met} compared with RFI_{growth} , probably due to the daily management for CH_4 emission measurement.

The linear regression model used to calculate RFI_{growth} explained 82% of the variation in DMI. This value was higher than those reported in the literature, with a variation of 60% for heifers fed grass silage (Fitzsimons et al., 2013); 66% for heifers fed grass silage and concentrate as supplement (Lawrence et al., 2012); 70% for crossbred steers receiving a high-corn diet (Freetly and Brown-Brandl, 2013); and

77% for heifers fed corn silage and a concentrate diet (Kelly et al., 2010). Apparently, in the present study, the coefficient of determination of the model used for the estimation of RFI is not associated with the dietary energy density, as reported by Fitzsimons et al. (2013). A lower coefficient of determination ($R^2 = 0.54$) was obtained for the estimation of RFI_{met} when the same diet was offered, explaining 54% of the variation in DMI. This value was higher than the 43% observed by Lancaster et al. (2009) for heifers fed alfalfa-based diet and concentrate, and the 38% observed by Freetly and Brown-Brandl (2013) for heifers fed a high-roughage diet. The short duration (32 d) of ADG measurement may have compromised the calculation of RFI_{met} . In that equation, ADG was not significant ($P = 0.07$) and $BW^{0.75}$ explained most of the variation in DMI.

When RFI is used as a measure of feed efficiency, efficient animals consume less than their inefficient counterparts for the same production performance (Fitzsimons et al., 2013). As a consequence, it would be expected that animals with low RFI would release less methane proportionally to their lower feed intake. However, studies have shown variations in methane emission between low- and high-efficiency animals. Fitzsimons et al. (2013) observed less methane emission (g/d and g/kg $BW^{0.75}$) in low- RFI_{growth} heifers and Hegarty et al. (2007) showed that steers selected for low RFI also have reduced daily methane emission (g/d). These results agree with the observations in the RFI_{met} test, in which Nellore bulls classified as low- RFI_{met} released less enteric methane (g/d) ($P = 0.024$). Taken together, the results suggest the potential selection of cattle for feed efficiency and reduced enteric methane emission. On the other hand, no difference ($P > 0.05$) in enteric methane emission (g/d and g/kg $BW^{0.75}$) was observed in the present study when it was compared between animals of low and high RFI_{growth} .

The methane emission data (g/d) are similar to those reported by Possenti et al. (2008), who observed emission of 147.5 g CH_4 /d in cattle fed coast-cross hay with 200 g/kg of leucaena, and lower than those estimated by Johnson and Johnson (1995) for beef cattle (164 to 194 g CH_4 /d). The values expressed as kg/year (51-53 kg CH_4 /kg year) agree with the estimates reported by Cederberg et al. (2009) for young cattle in Brazil (47-56 kg CH_4 /year), and by the IPCC (2006), which estimated an average emission of 49 kg CH_4 /year for young cattle (230 kg BW) in Latin America. These data corroborate the findings of Jones et al. (2011), who observed similar daily methane emissions (g/kg BW) in cows with low and high RFI grazing on low-quality pasture.

When methane emissions were expressed as unit of feed consumed (g/kg DMI during RFI_{growth}), high-efficiency animals (low- RFI_{growth}) released more methane (25.1 g/kg

DMI) than their low-efficiency counterparts (22.8 g/kg DMI) ($P < 0.05$). In this case, the enteric methane emission is probably related to higher digestibility and a higher ruminal fermentation rate, increasing the total production of short-chain fatty acids with a proportional increase in the production of methane. Previous research (Magnani et al., 2013) reported higher DM digestibility for low-RFI Nellore heifers than high-RFI heifers (49.14% vs 45.38%, respectively). Richardson et al. (1996) observed that steers and heifers with low or high feed efficiency tend to differ in their capacity to digest DM, by about one percentage unit (DM digestibility of 68%), and this difference in digestibility was responsible for 14% of the difference in DMI. However, digestibility and ruminal digestion products were not evaluated in the present study, but studies suggest that the efficiency of animals classified as low-RFI is associated with a greater digestive capacity (Herd and Arthur, 2009; Richardson and Herd, 2004). Freetly and Brown-Brandl (2013) suggested that methane emission may increase with increasing feed efficiency and that selection of cattle for increased feed efficiency will not necessarily reduce enteric methane emission.

The results reported by Freetly and Brown-Brandl (2013) also do not support the hypothesis that increased feed efficiency reduces methane emission. The authors observed that measures of feed efficiency, BW gain:DMI ratio, and RFI, are not associated with methane emission in cattle fed a high-corn diet (828 g/kg). When the animals were fed a high-roughage diet (600 g/kg of corn silage, 30 g/kg of alfalfa hay), RFI was not related to methane emission, but the association between BW gain:DMI ratio and methane emission was positive. According to the authors, the increase in the methane emission rate with increasing feed efficiency (BW gain:DMI) may have been due to the higher fermentation of feed, increasing nutrient availability and methane emission. In contrast, no differences in methane emission (g/kg DMI) were observed between animals classified as low- and high-RFI_{met} ($P = 0.915$), despite differences in DMI between low- and high-RFI_{met} animals (7.09 and 8.12 kg/d, respectively) and a moderate positive Pearson correlation ($r = 0.62$) between CH₄ (g/d) and DMI (kg/d). Likewise, regression analysis indicated that an increase of 1 kg in DMI was associated with an increase of 17 g/d in methane emission ($r = 0.38$). Fitzsimons et al. (2013) and Hegarty et al. (2007) also observed no difference in methane produced as a function of DMI between RFI classes; however, Nkrumah et al. (2006) observed that low-RFI steers released less methane per unit of DMI.

The methane emission values (expressed as g/kg DMI) estimated in the present study (20.1 to 25.1 g/kg DMI)

agrees with those reported in the literature for animals fed high-roughage diets. McGeough et al. (2010) observed methane emissions of 35.6 g/kg DMI in beef cattle fed grass silage plus 2.60 kg of supplemental concentrate DM, and 15.3 g/kg DMI for animals offered concentrate *ad libitum*. These results suggest that animals fed high-forage diets generally tend to release more methane (g/kg DMI) than animals offered high-concentrate diets (Janssen, 2010). In the present study, no difference in methane emissions, expressed as g/kg ADG during RFI_{growth} or RFI_{met}, was observed between more and less efficient animals ($P > 0.05$). This finding was expected, since no significant difference in ADG was observed during both studied periods ($P > 0.05$).

The loss of energy in methane form, defined as the percentage of enteric methane emitted and expressed as a function of gross energy intake (%GEI), was on average 6.5% during the RFI_{met} period. This value agrees with those predicted by the IPCC (2006) for beef cattle raised under tropical conditions (6.5% to 7.5%). However, these values are lower than those reported by McGeough et al. (2010) for continental crossbred steers fed corn silage-based diets (7.3% to 8.4% GEI) using SF₆ gas tracer techniques, and by Fitzsimons et al. (2013) for grass silage-based diets offered to Simmental heifers (12.6% GEI), with values established at the upper end of variation of 2% to 12% GEI as reported by Johnson and Johnson (1995).

High-efficiency animals show a significant reduction in DMI; however, it is not possible to confirm that more efficient animals release less enteric methane, since different results were obtained when enteric methane was compared between RFI_{growth} classes and RFI_{met} classes. These results may be expected, since the duration of the tests differed, as also did the number of days between each test and methane measurement. While RFI_{growth} was based on measurements obtained in the middle of the test, about 65 days before methane sampling, RFI_{met} was measured exactly during the measurement of methane emission. In addition, the period of 32 d to obtain RFI_{met} may not be sufficient for the accurate measurement of ADG (Wang et al., 2006). This would explain the Spearman correlations between traits obtained during both tests, which were high between BW^{0.75} and DMI and zero between ADG, resulting in a correlation of medium magnitude between RFI_{growth} and RFI_{met}, with evidence of re-ranking of the animals for RFI.

In view of the differences in enteric methane emission among studies, further research is needed to determine the effect of selection of high-efficiency animals (low RFI) on enteric methane emission by investigating different diets and phases of the animal lifetime and methods used for measuring enteric methane. Several mitigation strategies

have been proposed to reduce greenhouse gas emission, many of them designed to reduce enteric methane emission. The selection of animals with low DMI and similar ADG could be a strategy to reduce greenhouse gases emissions in the beef production system as a whole since these animals are highly efficient in feed utilization.

Conclusions

There is no evidence that high-efficiency animals release less enteric methane, even with lower dry matter intake and same performance than their inefficient counterpart.

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