University of São Paulo
"Luiz de Queiroz" College of Agriculture

Dietary strategy to reduce methane emission in Brazilian beef cattle production

Jacqueline Geraldo de Lima

Thesis presented to obtain the degree of Doctor in Science. Area: Animal Science and Pasture

Piracicaba
2014

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Zootechnics

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versão revisada de acordo com a resolução CoPGr 6018 de 2011

Advisor:
Profa. Dra. **PATRICIA MENEZES SANTOS**

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To my parents, my greatest encouragement and life example (love you);
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DEDICATE

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BIOGRAPHY

Jacqueline Geraldo de Lima was born on August 26, 1985 in Mococa, Brazil. She attended elementary and secondary school education in the city she was born. From 2004 to 2009 she studied at Federal University of Viçosa, Viçosa, Minas Gerais, in Brazil and obtained a BSc degree in Animal Science. From 2009 to 2010 she obtained a MSc degree in Forage Science. Her MSc thesis was about implantation of pastures via consortium of *Urochola brizantha* with bean or corn for silage under tillage or no-tillage system. In March 2011, she started her PhD in Animal Nutrition and Forage Science at Escola Superior de Agricultura “Luiz de Queiroz”, University of São Paulo, Piracicaba, São Paulo, in Brazil. In November 2012 to October 2013, she made her professional internship at Wageningen University Research Centre (Wageningen UR Livestock Research) in the Netherlands. The results are described in this thesis. During her PhD, she estudied the effect of improvement in diet quality by feeding supplementation on CH_4 emission in different production systems of beef cattle in Brazil, estimated by an empirical IPCC Tier 2 approach and by the dynamic, mechanistic approach currently applied as a Tier 3 approach in the Netherlands.

"As we acquire more knowledge, things not become more comprehensible, but more mysterious"

Albert Schweitzer

SUMMARY

RESUMO

Estratégia dietética para reduzir a emissão de metano em sistema produção de gado de corte no Brasil

No Brasil, a estimativa de emissão de metano no inventário nacional sobre a emissão de metano (CH_4) é realizada pela abordagem Tier 2, recomendada pelo Painel Intergovernamental sobre Mudanças Climáticas (IPCC). Embora o IPCC recomende o uso do Tier 3, uma abordagem mais complexa, a aplicação desta no Brasil é dificultada pela falta de dados consolidados para o desenvolvimento, avaliação e aplicação do modelo. O objetivo deste trabalho foi estimar o efeito da melhoria da qualidade da dieta na emissão entérica de $CH_{4,}$ em sistemas de produção de gado de corte brasileiros, pelos métodos Tier 2 e Tier 3. A emissão entérica de $CH_{4,}$ foi estimada em seis sistemas de produção de bovinos de corte, do desmame até abate. Os sistemas estudados abrangeram os métodos de alimentação mais praticados na produção de carne bovina brasileira. A qualidade da alimentação e desempenho animal foram estimados baseados em estudos publicados na literatura. Ambas as abordagems Tier 2 e 3 estimaram efeito da suplementação sobre a emissão de CH_4. As estimativas do Tier 2 e 3, no sistema de abate aos 44 meses, apresentaram maior emissão de CH_4 entérico comparados aos outros sistemas, resultando em valores de 168 e 145 kg de CH_4 por animal, respectivamente. Por outro lado, o sistema de abate aos 14 meses, apresentou menor emissão de CH_4, comparados aos outros sistemas, em valores de 35 e 31 kg de CH_4 por animal abatido, respectivamente. A tendência geral foi um aumento de emissão de CH_4 com o aumento da idade de abate. Usando a abordagem Tier 3 para as condições brasileiras resultou valores menores de CH_4 entérico em comparação a Tier 2. Os valores Ym (fração de ingestão de energia bruta emitido como CH_4) estimados pela Tier 3, nas diferentes estações, variou entre 0,044 e 0,070, e para diferentes sistemas de produção entre 0,049 e 0,058. Por outro lado a média para todo o período de crescimento foi 0,065 para Tier 2. Essas estimativas devem ser confirmados com dados in vivo obtidos em condições locais, com intuito de melhorar o modelo Tier.

Palavras-chave: Bovinos de corte; Efeito estufa; Emissão de metano; Mitigação; Modelagem

ABSTRACT

Dietary strategy to reduce methane emissions in Brazilian beef cattle production

In Brazil, estimate of methane (CH_4) emission for the National Greenhouse Gas Inventory is carried out using the empirical Tier 2 approach published by the Intergovernmental Panel on Climate Change (IPCC). Although, IPCC recommends the use of a more specific, mechanistic Tier 3 approach, this is hampered by a lack of consolidated data for development, evaluation and application of such a Tier 3 approach. The purpose of the present modelling study was to evaluate whether a Tier 3 approach instead of the Tier 2 approach has merit in estimating the effect of improvement of diet quality by feeding supplements on CH_4 emission, calculated by both a Tier 2 and an extant Tier 3 approach. Six systems of beef cattle production in Brazil were considered which differed inage at slaughter mainly due to diet quality (ranging from 14 to 44 months). The systems studied encompass most of the range of slaughter age and feeding methods observed and the differences between them can be considered realistic for variation in current Brazilian practice of beef production. Estimates of feed quality and animal performance were based on published Brazilian studies and on data from a Brazilian inventory on enteric CH_4. Both Tier 2 and Tier 3 approaches estimated a large variation in CH_4 emission for the six production systems. The highest level of enteric CH_4 emission (168 and 145 kg per slaughtered animal, estimated with the Tier 2 and Tier 3 approach, respectively) was estimated for the system with slaughter after 44 months and the lowest with slaughter after 14 months (35 and 31 kg per slaughtered animal, estimated with the Tier 2 and Tier 3 approach, respectively). The general trend was a profound increase of CH_4 emission with increase of age-at-slaughter. Methane estimates depended strongly on the modelling approach adopted. Using the Tier 3 approach in the present study with the assumptions made for the six Brazilian beef production systems indicated substantially lower estimates of enteric CH_4 compared to the IPCC Tier 2 approach. The Ym values (fraction of gross energy intake emitted as CH_4) estimated by the Tier 3 approach for separate growing periods (seasons) within the different systems ranged between 0.044 and 0.070, and between 0.049 and 0.058 when averaged for the whole growing period (cf. 0.065 with Tier 2). Model estimates should be confirmed by evaluation against independent in vivo data obtained under local Brazilian conditions of beef production.

Keywords: Beef cattle; Greenhouse gas; Methane emission; Mitigation; Modelling

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1 INTRODUCTION

There are concerns about the contribution of ruminant production to climate change due to methane (CH_4) that is produced by enteric fermentation and emitted as a greenhouse gas (GHG) (STEINFELD et al., 2006). In Brazil, the herd size of cattle is estimated to be around 200 million head, and therefore is the biggest national commercial herd worldwide. The animals are mostly kept under pastoral conditions (FERRAZ; FELICIO, 2010). Enteric fermentation was the third contributor in terms of carbon dioxide equivalents (CO_2-eq), but it is also by far the first contributor to CH_4 emission (CERRI et al., 2009). Enteric fermentation and the emission of CH_4 from the rumen and hindgut have been shown to be affected by the composition of the feed. Improving diet digestibility will increase animal productivity and the efficiency of converting feed into animal products, and as a consequence, will reduce CH_4 per unit of animal product with tenths of percent units depending on the range of conditions that are compared (ECKARD et al., 2010).

Mathematical models are used to evaluate the effects of mitigation strategies on enteric CH_4 emission. Empirical models based on dietary composition predicted CH_4 emission satisfactorily (ELLIS et al., 2007), but they lack the biological basis and mechanisms underlying enteric fermentation. When the aim is to address the mechanism and complexity of the digestive process in the rumen, more mechanistic models are a good alternative and helpful tool. National inventories (e.g. Brazil) generally use empirical models adapted from the Tier 2 approach as recommended by the Intergovernmental Panel on Climate Change (INTERNATIONAL PANEL ON CLIMATE CHANGE - IPCC, 2006). However, the IPCC recommends a specific Tier 3 approach for key sources of GHG emissions, provided that knowledge and activity data are available, in order to obtain a more precise estimate of enteric CH_4 emission. A Tier 3 approach must be evaluated against experimental data and must make use, as much as possible, of local activity data instead of generic data for inventory purposes. Since 2005, a country-specific modelling approach has been used as Tier 3 to estimate CH_4 emission in dairy cows for the Dutch national inventory of GHG emissions (BANNINK et al., 2011). A similar approach may be adopted by other countries, but it is often impaired by the lack of consolidated data for the evaluation and application of such a Tier 3 approach, as is the case in Brazil for instance (BUSTAMANTE et al., 2012). Nevertheless, a predecessor and simplified version of the model that is currently in use as a Dutch Tier 3 approach already has been developed and applied to study the effects of dietary supplementation of sugar cane diets in Brazil (DIJKSTRA et al., 1996a, 1996b). A Tier 3 type of modelling approach has not been applied so far for enteric CH_4 inventory purposes in Brazil, nor has its applicability for such purposes been investigated and directly compared to the Tier 2 approach that is currently used for Brazilian GHG inventory.

The aim of this study was 1) to study the impact of a variety of beef production systems, differing in moment and level of dietary supplementation, and representative for the variation encountered in current Brazilian beef systems, and 2) to make use a dynamic, mechanistic model of enteric fermentation currently used as a Tier 3 approach in the Dutch GHG inventory in comparison with the Tier 2 as default approach in current GHG inventory. .

2 LITERATURE REVIEW

2.1 Enteric Mehane Emission by Brazilian Beef Cattle and Mitigating Strategies

The livestock sector represents a significant source of greenhouse gas (GHG) emissions worldwide by generating carbon dioxide (CO_2), CH_4, and nitrous oxide (N_2O) from enteric fermentation and manure decomposition (HISTROV et al., 2013). Particular attention has been paid to mitigating CH_4 emission from developing countries (Asia, Africa, and Latin America) because they are least efficient, as they produced 47.3% of ruminant meat and milk but 69% of enteric CH_4 emissions (Food and Agriculture Organization of the United Nations –FAO, 2010). Brazil has the world's second largest cattle herd with about 209 million heads, which are mostly raised in extensive pastures (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA - IBGE, 2007) and thereby make an important contribution to global GHG emissions. Enteric CH_4 emission is the most significant among the Brazilian GHG emissions, accounting for 63% of all CH_4 emission produced by Brazilian agriculture (BRASIL, 2010).

Most of Brazilian beef production arises from animals grazing tropical grasses which are characterized by native and mainly introduced grasses. Nonetheless, the combination of poor soils, marked season rainfall and introduced C_4 grasses affect the avaibility, quality and digestibility of forage throughout the year (IBGE, 2007). The most of production, diet supplementation is needed in the dry season, but a very small number of farmers do so due to cost constraints (MILLEN et al., 2013). Feedlot operations are usually short, on average around 70 days during the dry season, when pasture availability is decreased (MILLEN et al., 2009). Improving diet quality by the addition of grain to a forage diet can improve animal performance and reduce CH_4 production, which can therefore improve feed efficiency (HRISTOV et al., 2013). Several dietary and farm system strategies to mitigate enteric CH_4 emission from ruminants include strategies such as the improvement of forage quality by intensive management of pastures, the use of grain and concentrate, the use of pasture legumes, and the addition of tannins, saponins, essential oils, saturated and unsaturated fats and oils, ionophores, nitrate compounds, yeasts of various origins, which were reported by Grainger and Beauchemin (2011).

Increasing the dietary proportion of concentrate usually reduces CH_4 losses (HOLTER; YOUNG, 1992; SHIBATA et al., 1992; LOVETT et al., 2003; IPCC, 2006). The improvement in the diet quality by the addition of grain results in a reduced rumen pH, thus favoring the production of propionate rather than acetate in the rumen (MCALLISTER; NEWBOLD, 2008) and, consequently, reducing the proportion of dietary energy converted to

CH_4 (BLAXTER; CLAPPERTON, 1965). Linear decreases in CH_4 production by adding concentrate to forage diets have been reported for lactating dairy cows and beef cattle (MCGEOUGH et al., 2010; AGUERRE et al., 2011; HRISTOV et al., 2013). However, feeding a high-concentrate diet is impractical with the recent high grain prices and the shortage of human food in developing countries (SHIBATA et al., 2010); also, a high-concentrate diet can lead to added N_2O and transport emissions during the grain production processes (ECKARD et al., 2010).

Previous estimates of the efficiency of livestock production in Brazil indicate that the reduction in slaughter age through adequate pasture management and feedlot strategic finishing over 90 days can significantly reduce emission intensity, even when considering all sources of emissions for production and distribution (BERNDT;TOMKINS, 2013).

Canesin (2009) evaluated the effects of supplementation frequency (offered daily or from Monday to Friday or in alternate days) on beef cattle on enteric CH_4 emissions in June, September and November. The CH_4 emissions were 7.4 g h^{-1} and 178 g day^{-1} (from Monday to Friday) in September, and 13.2 g h^{-1} and 316.1 g day^{-1} (from Monday to Friday) in November. Demarchi et al. (2003) showed that CH_4 emissions varied as a function of season and forage quality. Mean CH_4 emissions were 102.3, 136.5, and 209.9 g day^{-1} in winter, spring, and summer, respectively. Similarly, Primavesi et al. (2004) showed that CH_4 emissions is influenced by animal category and the intensity of management in the production system. Measurements were performed in the summer with Holstein and Holstein x Zebu crossbred dry cows that were grazing unfertilized *Urochloa* grass and fertilized *Panicum maximum* grass. The CH_4 emissions were 7.6 g h^{-1} and 181 g day^{-1}; 12.3 g h^{-1} and 295 g day^{-1}, respectively.

Therefore, considering the importance of the environmental impact of GHG emissions in Brazil, the search for more efficient livestock systems, while aiming to reduce GHG emissions and increase animal production, may be a strategy to reduce barriers to Brazilian livestock product trading (BERCHIELLI et al., 2012).

2.2 Modeling Approaches to Estimate Enteric Methane Emission by Ruminants

Several indirect methods have been developed to estimate CH_4 emission from animals (ELLIS et al., 2010) because the measurement of CH_4 production in animals requires complex and often expensive equipment (KEBREAB et al., 2008). They can be classified as "linear" or "non-linear" models according to the type of equations that are used. They can also be classified as "empirical" or "mechanistic" according to the degree of explanation they describe or estimate. Furthermore, they can be classified as either "static" or "dynamic" according to their behavior over time (THOLON; QUEIROZ, 2009).

Some models have been developed specifically to estimate CH_4 emission from animals (KRISS, 1930; AXELSSON, 1949; BLAXTER; CLAPPERTON, 1965; MOE; TYRRELL, 1979; MILLS et al., 2003; ELLIS et al., 2007) and other models have been modified or adapted to calculate to CH_4 emission from rumen fermentation (e.g. DIJKSTRA et al., 1992; MILLS et al., 2001; BANNINK et al., 2008, 2011). Empirical and mechanistic models quantify enteric fermentation mainly by feed intake (ELLIS et al., 2007; KEBREAB et al., 2010); empirical models relate nutrient intake directly to CH_4 output, and dynamic mechanistic models estimate CH_4 emission through mathematical descriptions of the rumen fermentation process and methanogenesis (KEBREAB et al., 2006). Although empirical models require few and easily accessible inputs, they are valid just for the range of conditions under which they were developed (KEBREAB et al., 2008). Mechanistic models may provide more appropriate estimates of enteric CH_4 production because such models are able to represent various factors related to microbial activity and methanogenesis (ELLIS et al., 2008). However, many input variables are required and some of them are usually unavailable (ELLIS et al., 2007).

National and global level CH_4 production is estimated according to the IPCC guidelines (IPCC, 2006). IPCC methods follow the hierarchy of detail and complexity (referred to as Tier 1, 2, and 3 approaches) from the most simple to the most complex.

The Tier 1 approach is characterized by simple calculations based on default emission factors (EF) drawn from previous studies and available animal population data. The Brazilian beef cattle estimate of EF is 56 kg CH_4 $hd^{-1}year^{-1}$ **(**IPCC, 2006). The Tier 2 approach requires country-specific information on livestock characteristics and manure management practices. It is recommended for countries with large cattle populations. The CH_4 emission is calculated based on gross energy intake (GEI, in terms of energy content, MJ d^{-1}) and CH_4 conversion rates (% GEI).

Nevertheless, empirical models such as the Tier 2 approach are frequently chosen because these models require lower numbers of inputs and more easily accessible. However, CH_4 estimation is hampered because the proportion of GEI emitted as CH_4 is assumed to be constant while neglecting to account for the variation in diet that is unrelated to dry matter intake (DMI), variation in the site of digestion of carbohydrates and protein, and the lack of fermentation of dietary fat. Such errors may lead to incorrect mitigation recommendations (BANNINK et al., 2013). Ellis et al. (2010) verified that the accuracy of determining enteric CH_4 emission when using a fixed EF is lower, and thus the application of fixed EF in whole farm models may introduce substantial error into inventories of GHG.

Cardoso (2012) also simulated the effects of the intensification of beef production systems in Brazil on GHG emissions by applying the IPCC Tier 2 approach. Four scenarios were established: (1) animals spend the entire cycle in areas of degraded pastures in an extensive system, (2) animals spend the entire cycle on improved pastures, but under an extensive system, (3) animals are raised on extensive improved pastures and supplemented in growing and fattening systems, and (4) animals are raised on pastures with intensive finishing on high-grain diets. The estimates of GHG emissions were based on national studies of the characteristics and husbandry for each scenario. Using the IPCC Tier 2 approach, the annual amount of CO_2-eq per kg carcass-eq produced in scenario 2 was 35.5% lower when compared to scenario 1, 18.9% less in scenario 3 when compared to scenario 2, and 19.6% lower in scenario 4 when compared to scenario 3. Monteiro (2009) also simulated the progressive intensification of beef production systems based on the IPCC Tier 2 approach while considering (1) an extensive grazing system, (2) an intensive grazing system, and (3) an intensive grazing system with finishing in a feedlot. When considering the inputs, the estimated emissions based on CO_2-eq per kg carcass-eq produced were 19.88, 14.11 and 12.3, respectively; this result indicates that a strategic feedlot period equivalent to 90 days could reduce the slaughter age and associated emissions by a significant 38%.

However, to obtain more reliable estimates of enteric CH_4 emission, the IPCC recommends a Tier 3 approach. A Tier 3 approach must be evaluated against experimental data, and must make use, as much as possible, of local activity data instead of generic data for inventory purposes. In the Netherlands, a country-specific modelling approach was developed to estimate enteric CH_4 emission by dairy cows annually, and it has been applied as a Tier 3 approach in the Dutch national inventory of GHG emissions since 2005 (BANNINK et al., 2011). A similar approach may be adopted by Brazil, but it is often impaired by the lack of consolidated data for development, evaluation, and application (BARIONI et al., 2011). This

Tier 3 type of modelling approach has not been applied so far for enteric CH_4 inventory purposes in Brazil, nor has its applicability for such purposes been investigated and compared to the Tier 2 approach that is currently in use in Brazilian GHG inventory.

Therefore, deciding which model to use to quantify CH_4 emission depends on the origin of data, the level of detail required by the model chosen, and the specific aim(s) of the model (at the diet or ingredient level, at the animal and digestive level, or at the rumen fermentation level). Thus, if the aim is to estimate enteric CH_4 emission on a farm or regional scale, the Tier 2 approach or another empirical model are frequently used (SCHILS et al., 2007), although there are exceptions to this (BEUKES et al., 2011). Nonetheless, if the aim is to detect the impact of the mitigation strategies to reduce enteric CH_4 emission, the mechanistic models are required (KEBREAB et al., 2006; ELLIS et al., 2007; BANNINK et al., 2013).

3 METHODS

3.1 Characterization of Beef Cattle Systems

To evaluate the effects of improving the diet quality by feeding diet supplements on CH_4 emission in different beef cattle systems, six types of Brazilian beef cattle systems were formulated, based on previous classifications made by specialists. Diet ingredients and supplements intake were adapted from Carmo Vieira (2011), Roth et al. (2013), and Sampaio (2011). The first and second systems used crossbreed Nellore and Angus animals (F1). The six beef cattle systems shown in Table 1 differ in their supplemental feeding strategies and the slaughter age of beef cattle.

Table 1 - Characterization of six beef cattle systems classified according to their slaughter age of beef cattle and feeding method

Variable	Slaughter age (months)					
	14	20	24	30	36	44
Breed	F1[1]	F1	Nellore	Nellore	Nellore	Nellore
Age at weaning (days)	240	240	240	240	240	240
Weaning weight (kg)	240	240	200	200	170	170
Slaughter age (days)	407	587	695	907	1065	1335
Slaughter weight (kg)	475	495	528	544	539	537
First dry diet[2]	TMR	EPS	DPS	DPS	US	US
First wet diet[3]		EPS	WPS	MS	MS	MS
Second dry diet			TMR	DPS	US	US
Second wet diet				WPS	MS	MS
Third dry diet					TMR	US
Third wet diet						MS

[1] Crossbreed Angus × Nellore;
[2]TMR, total mixed ration; EPS, energetic-proteic supplementation; DPS, dry period protein supplementation; US, urea with mineral salt;
[3] WPS, wet period protein supplementation; MS, mineral salt (*ad libitum*).

The quantity and type of feed supplementation were as follows: total mixed ration (TMR) with a slaughter age of 14 months (feedlot finishing; M14TMR); an energetic-proteic supplementation (EPS) at 7 g kg^{-1} body weight (BW) during the dry season and 5 g kg^{-1} BW during the wet season with a slaughter age of 20 months (pasture-finishing; M20WPS); a protein supplementation during the dry (DPS) and wet seasons (WPS) at 1 g kg^{-1} BW ending with a TMR (feedlot finishing) and a slaughter age of 24 months (M24TMR); *ad libitum* mineral salt supplementation (MS) at 1 g kg^{-1} BW of DPS during the first and second dry seasons combined with WPS at 1 g kg^{-1} BW during the wet season and a slaughter age of 30 months (pasture-finishing; M30WPS); a urea supplementation with mineral salt (US) at 60 g per animal with mineral salt during the dry season and *ad libitum* MS during the wet season, ending with a TMR and with a slaughter age of 36 months (feedlot finishing; M36TMR); a 60 g per animal US during the dry season and *ad libitum* MS during the wet season with a slaughter age of 44 months (pasture-finishing; M44WPS).

3.2 Dietary Ingredients, Chemical Composition and Digestibility

The data on chemical composition and *in situ* degradation characteristics of concentrates and supplements were taken from Tedeschi et al. (2002) unless indicated otherwise. The data on chemical composition were used to calculated the carbodydrate and protein fractions, based on equations from the Cornell system level 2, which defines carbohydrate and protein fractions (SNIFFEN et al., 1992; FOX et al., 2004) and *in situ* degradation characteristics as comparable to the inputs required by the Tier 3 approach that were used in the present study. In the Cornell system, carbohydrates are divided into fractions A, B1, B2, and C, where A is the sugar fraction with the fastest fractional degradation rate of all fractions, B1 is the fraction of starch and soluble structural carbohydrates (such as pectin) with an intermediate fractional degradation rate, B2 is the potentially degradable part of NDF with a slow fractional degradation rate, and C is the undegradable part of NDF. Crude protein is also divided into fractions A, B1, B2, B3, and C, where A is non-protein nitrogen (NPN; such as ammonia and nitrate), B1 is the soluble protein with a high fractional degradation rate, B2 is the buffer insoluble protein minus the insoluble protein in neutral detergent with an intermediate fractional degradation rate, B3 is the insoluble protein in neutral detergent but soluble in acid detergent with a slow fractional degradation rate, and C is the insoluble protein in the acid detergent and is undegradable (SNIFFEN et al., 1992; FOX et al., 2004). The chemical composition of the ingredients in the concentrates and supplements are shown in

Table 2 for each beef cattle production system and was used in the present study as an input for the Tier 3 approach (See 3.4).

Table 2 – Diet ingredients (% of DM), dietary chemical composition (g kg^{-1} DM), and degradation fractions of NDF, CP and starch (g kg^{-1} substrate) and fractional degradation rate of degradable fraction (kd) of NDF, CP and starch (d^{-1}) for the forages, concentrate ingredients and dietary supplements used in six beef systems (continue)

	Slaughter age (months)							
	14	24	36	20	24	24;30	30;36	36;44
Diets	TMR[1]	TMR	TMR	EPS[2]	DPS[3]	WPS[4]	MS[5]	US[6]
Percentage of roughage in diet, % in feed DM	50	50	60	97	99	99	100	100
Concentrate Ingredients (%)								
Corn silage	50.0	50.0	60.0	-	-	-	-	-
Corn grain	32.1	-	29.2	-	-	-	-	-
Cottonseed meal	-	5.8	-	31.9	41.9	44.3	-	-
Citrus pulp pellet	-	26.4	-	56.0	37.0	41.9	-	-
Wheat meal	8.0	-	-	-	-	-	-	-
Soybean hulls	-	12.5	-	-	-	-	-	-
Soybean meal	7.4	1.9	10.0	-	-	-	-	-
Urea	0.5	1.5	0.4	3.4	12.4	4.9	-	31.6
Calcium bicarbonate	1.0	-	0.4	-	-	-	-	-
Sodium chloride	-	-	-	3.6	3.5	3.7	-	-
Mineral Premix	0.7	1.8	-	5.0	5.0	5.0	-	-
Mineral Salt	-	-	-	-	-	-	100.0	68.4
Monensin	0.3	0.2	-	0.1	0.2	0.2	-	-
Chemical composition								
Crude protein	12.9	14.3	12.9	25.6	53.4	33.5	-	88.8
Ether extract	2.5	2.6	3.0	1.6	1.4	1.5	-	-
Carbohydrate	79.3	78.9	80.9	65.0	54.3	59.8	-	-
Non structure carbohydrate	43.9	36.7	43.7	39.8	28.0	31.4	-	-
Neutral detergent fiber	35.4	42.2	37.2	25.1	26.4	28.4	-	-
Ash	5.6	6.9	3.9	13.9	13.4	14.0	100.0	68.4

Table 2 – Diet ingredients (% of DM), dietary chemical composition (g kg^{-1} DM), and degradation fractions of NDF, CP and starch (g kg^{-1} substrate) and fractional degradation rate of degradable fraction (kd) of NDF, CP and starch (d^{-1}) for the forages, concentrate ingredients and dietary supplements used in six beef systems (conclusion)

	Slaughter age (months)							
	14	24	36	20	24	24;30	30;36	36;44
Diets	TMR[1]	TMR	TMR	EPS[2]	DPS[3]	WPS[4]	MS[5]	US[6]
Degradation characteristics								
Carbohydrate fraction[7]								
A	3.5	6.4	5.5	5.6	2.7	3.0	-	-
B1	53.1	57.9	49.7	50.6	45.7	52.3		
B2	34.7	23.6	28.7	28.2	41.4	36.0	-	-
C	8.7	12.1	16.1	15.7	10.2	8.8	-	-
Protein fraction[8]								
A	26.6	45.1	24.4	45.1	69.0	47.4	-	100.0
B1	11.4	4.8	13.6	5.8	3.6	6.1	-	-
B2+B3	57.4	44.3	57.0	45.8	26.2	44.3	-	-
C	4.6	5.8	5.03	3.2	1.3	2.2	-	-
kd Carbohydrate								
B1	10.6	20.2	10.6	29.4	28.9	28.9	-	-
B2	2.3	2.9	2.2	5.3	4.9	4.9	-	-
kd Protein								
B2+B3	2.7	3.2	2.5	5.5	5.9	5.9	-	-

[1] TMR, total mixed ration;[2] EPS, energetic-proteic supplementation;[3] DPS, dry period protein supplementation;[4] WPS, wet period protein supplementation (slaughter 24 and 30 months);[5] MS, mineral salt (*ad libitum*) (slaughter 36 and 44 months); [6] US, urea with mineral salt (slaughter 36 and 44 months);[7] According to Cornell terminology: Carbohydrate fraction = A+B1 (sugars + starch) + B2 (available cell wall) + C (unavailable cell); [8] Protein fraction = A (nonprotein nitrogen) + B2+B3 (buffer insoluble protein minus the protein insoluble in neutral detergent + insoluble in neutral detergent but soluble in acid detergent), C (protein insoluble in the acid detergent)

It was assumed that the forage grass *Urochloa brizantha* cv. Marandu was produced without fertilization or irrigation (FERREIRA et al., 2013). The quality and availability of forage varies during the dry and wet seasons, thereby resulting in the need to use supplements to improve production and to decrease the slaughter age. The composition of the forage grass was determined based on studies by Canesin (2009), Casagrande et al. (2011), Hernández et al. (2002), Malafaia et al. (1998), Moraes et al. (2006), Morais et al. (2009), Oliveira et al. (2012), Queiroz et al. (2011), Sá et al. (2010), Tedeschi et al. (2002) and Velásquez et al. (2010). In those studies, the chemical composition, the carbohydrate and protein fractions, as well as the *in situ* degradation characteristics were evaluated for *Urochloa brizantha* cv.

Marandu. The averages of the values that were reported in these studies for the wet and dry seasons were used in the present study as an input for the Tier 3 approach (Table 3).

Table 3 - Mean chemical composition (% of DM), carbohydrate and crude protein degradation fractions (% of DM) and fractional degradation rate (kd) of NDF (B2) and CP (B2+B3) (d^{-1}) of *Urochloa brizantha* cv. Marandu during dry and wet seasons based on Brazilian data according to original estimates (Org) and adapted estimates (see 3.4 for further explanation) based on the comparison of Tier 3 predicted and Tier 2 adopted DM digestibilities

Season	*Chemical composition*					
	CP[1]	EE[2]	CHO[3]	NSC[4]	NDF[5]	Ash
Dry	5.8	1.6	84.8	12.4	72.4	7.8
Wet	9.6	1.4	80.7	12.4	68.3	8.3
	Carbohydrate fraction[6]					
	A+B1	B2	C			
Dry	15.0	66.0	19.0	-	-	-
Wet	15.5	67.8	16.7	-	-	-
	Protein fraction[7]					
	A	B1	B2+B3	C		
Dry	14.6	21.1	56.4	7.9	-	-
Wet	19.0	21.9	49.7	9.4	-	-
	Fractional degradataion rate (kd) kd fraction B2 Carbohydrates					
Dry		3.8				
Wet		5.0				
	Fractional degracation rate (kd) fraction (B2+B3) Protein					
Dry			2.1			
Wet			2.6			

[1] CP, crude protein;[2] EE, ether extract;[3] CHO, carbohydrate; [4] NSC, non structure carbohydrate; [5] NDF, neutral detergent fiber; [6] Carbohydrate fraction = A+B1 (sugar + starch) + B2 (available cell wall) + C (unavailable cell); [7] Protein fraction = A (nonprotein nitrogen) + B2+B3 (buffer insoluble protein minus the protein insoluble in neutral detergent + insoluble in neutral detergent but soluble in acid detergent) + C (protein insoluble in the acid detergent)

3.3 IPCC Tier 2 Approach to Estimate Enteric Methane Emission

Enteric CH_4 emission was calculated according to the IPCC guidelines for the Tier 2 approach (IPCC, 2006). Diets digestibilities were defined for six Brazilian beef cattle systems (Table 4) based on GOUVELLO et al. (2010) and specialists experience and were used to estimate the feed intake as an input for the Tier 2 approach. Dry matter intake was backcalculated from animal performance and diet digestibility corresponding to Tier 2 methodology (IPCC, 2006). The DMI was calculated for each month, except for biweekly estimates in the transitions between dry and wet seasons (Table 5). The gross energy intake associated with the feed intake that covers an animal's net energy requirements was used to calculate CH_4 emission with the Tier 2 approach. A gross energy value of 18.45 MJ kg^{-1} of dry matter intake (DMI) was assumed. An updated conversion factor of GEI to CH_4 (Ym) of 6.5% (IPCC, 2006) was applied to all diets. Calculated CH_4 energy lost was converted to kg CH_4 emission assuming a caloric value of 55.65 MJ kg CH_4^{-1}.

Table 4 - Assumed total tract DM digestibility (%) adopted with the model inputs for the Tier 2 approach for different growing periods, next to predicted total tract DM digestibility as an outcome of the Tier 3 approach when based on calculations using the original estimates of the *in situ* degradation characteristics for forage (Orig) or adapted estimates (Adap) as a model input (see 3.4 for further explanation)

	Slaughter age (months)																	
	14			20			24			30			36			44		
	Tier2	Tier3		Tier2	Tier3		Tier2	Tier3		Tier2	Tier3		Tier2	Tier3		Tier2	Tier3	
		Orig	Adap		Orig	Adap		Orig	Adap		Orig	Adap		Orig	Adap		Orig	Adap
	Total tract DM digestibility (%)																	
First dry	72	73	73	55	69	60	55	74	58	55	70	58	55	67	54	55	66	54
First wet				60	75	63	60	82	62	60	76	62	60	76	61	60	75	61
Second dry							70	76	76	55	70	59	55	70	56	55	67	56
Second wet										60	75	62	60	76	62	60	75	62
Third dry													72	71	71	55	67	56
Third wet																60	75	61

Table 5 - Average dry matter intake (kg DM d^{-1}) as an input for the Tier 2 and Tier 3 approaches for different growing periods

	Slaughter age (months)					
	14	20	24	30	36	44
	Average dry matter intake (kg DM d^{-1})					
First dry	9.7	8.4	6.4	6.4	4.2	4.2
First wet		12.6	9.5	8.9	6.2	6.2
Second dry			12.4	9.8	6.1	6.1
Second wet				13.1	7.8	7.8
Third dry					12.0	9.0
Third wet						13.0

3.4 A Tier 3 Approach to Predicting Enteric Methane Emission

The model that was applied as a Tier 3 approach to the inventory of GHG emissions from dairy cattle in the Netherlands (BANNINK et al., 2011) is a mechanistic, dynamic model representing the fermentation processes in the rumen and hindgut. The basal rumen fermentation model was developed by DIJKSTRA et al. (1992). The model was extended by MILLS et al. (2001) to include a representation of hydrogen balance and methanogenesis, while also including a representation of fermentation in the hindgut. The representation of volatile fatty acid production was updated according to BANNINK et al. (2008). The model requires inputs for DMI (kg d^{-1}), chemical composition of dietary DM and *in situ* rumen degradation characteristics of starch, NDF, and CP while excluding the ammonia fraction (BANNINK et al., 2011). Chemical fractions identified were sugars (SU), starch (ST), neutral detergent fiber (NDF), crude protein (CP), ammonia (including non-protein-N), crude fat (EE), ash and, in the case of the silages, organic acids. The remainder of DM not explained by these chemical fractions was added NDF and SU on 50/50 basis for starch-poor products, and added to NDF and ST on 50/50 basis in starch-rich products.

Degradation characteristics include a washable fraction W, a potentially degradable fraction D, an undegradable fraction U (all in g kg^{-1} substrate), and a kd for the fractional degradation rate of D (d^{-1}). Estimates of these degradation parameters were derived from *in situ* degradation characteristics were derived from databases on the degradation of feeds in nylon bags, which were incubated in the rumen of rumen-fistulated cows (Table 2 and 3).

The Tier 3 inputs include W (washable fraction), D (potentially degradable fraction), U (undegradable fraction), and kd (fractional degradation rate of D) for starch, NDF, and CP. These inputs were calculated based on the *in situ* degradation characteristics in the Cornell system (Tables 2 and 3) while assuming that for carbohydrates, A equals soluble carbohydrates, B1 equals the sum of the W and D (U nonexistent) of starch, B2 equals the D of NDF, and C equals the U of NDF. Additional assumptions were made on the distinction between W and D of starch; for corn silage W=400 and D=600, for corn grain W=300 and D=700, for cottonseed meal W=1000 and D=0, for whole cottonseed W=1000 and D=0, for citrus pulp pellet W=500 and D=500, for wheat meal W=400 and D=600, for soybean hulls W=1000 and D=0, and for soybean meal W=1000 and D=0. For protein, A was considered to equal ammonia (non-protein-N) content, B1 to equal W, the sum of B2 and B3 to equal D, and C to equal U.

The original estimates for the *in situ* degradation characteristics of forages (Orig) yielded estimations for total tract DM digestibility, which were far higher than the ones that were adopted for the Tier 2 approach (Table 4). This appeared to be strongly associated with the proportion of grass forage in the diet, and therefore degradation characteristics were adapted (Adap) for grass forage (Table 3) to allow for a realistic prediction of digestibility of CP, NDF and DM, thereby allowing for a useful comparison between CH_4 predition by the Tier 2 and Tier 3 approaches. The adaptation included the reduction by 50% the original values of D and kd of NDF and CP of grass forage during the wet as well as the dry season.

3.5 Models Outcomes and Related Calculations

The CH_4 emission was calculated by the Tier 2 and Tier 3 approach per season with emission intensities estimated as CH_4 from cumulated DMI for the whole growth period from weaning to slaughter (kg CH_4 kg^{-1} cumulated DMI) and as CH_4 per kg of average daily gain (ADG) (kg CH_4 kg^{-1} ADG) and per kg of carcass produced (kg CH_4 kg^{-1} carcass) considering whole carcass weight. It was hence assumed there is no CH_4 emission before weaning as recommended by the IPCC guidelines (IPCC, 2006).

4 RESULTS

4.1 Effects of Enhanced Diet Quality and Animal Productivity on Methane Emission

Average DMI, average daily gain (ADG), carcass yield, carcass weight, and the predictions of CH_4 emission for cumulated DMI per ADG, or per kg carcass that were produced with the Tier 2 and Tier 3 approaches (without and with adaptation of forage *in situ* degradation characteristics; Orig and Adap, resp.) are shown in Table 6. The improvement in diet quality with feeding supplementation resulted in large differences in predicted CH_4 emission between animal systems, up to a maximum difference of 133 and 114 kg CH_4 per animal slaughtered with the Tier 2 and Tier 3 (Adap) approaches, respectively. Feedlot finishing during the dry seasons in the M14TMR, M24TMR, and M36TMR production systems resulted in a 8, 3, and 7% lower average DMI (kg d^{-1}), respectively, when compared to pasture–finishing in the next wet season (M20WPS, M30WPS, M44WPS). There were 54, 32, and 29% lower CH_4 emission per cumulated DMI (kg), a 50, 28, and 31% lower CH_4 emission per kg ADG, and a 48, 32, and 32% lower CH_4 emission per kg carcass.

The CH_4 emissions intensities of the M14TMR (feedlot system) system were predicted to be 72, 56, and 70% lower than M36TMR (no protein and energy supplementation) with the Tier 2 approach when expressed per cumulated DMI, per kg ADG, or per kg carcass produced, and 68, 52, and 65% lower with the Tier 3 (Adap) approach, respectively. Intermediate values were calculated for M24TMR with protein supplementation; predictions for M14TMR were 60, 45, and 57% lower with the Tier 2 approach and 58, 44, and 52% with the Tier 3 approach, respectively. For the pasture-finishing systems, the estimated CH_4 emission for cumulated DMI, per kg ADG or per kg carcass for M20WPS (energy and protein supplementation) was 53, 35, and 53% lower than for M44WPS (no supplementation). For M30WPS (with protein supplementation only) the estimated CH_4 emission for cumulated DMI, per kg ADG, or per kg carcass produced were lower by 40, 18, and 34% with the Tier 2 approach, and 39, 19, and 33% lower with the Tier 3 approach, respectively.

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Table 6- Average dry matter intake (DMI), average daily gain (ADG), carcass yield, carcass weight, and CH_4 emissions per unit of cumulated DMI or ADG and carcass basis as calculated according to the IPCC Tier 2 and Tier 3 approaches (calculations with the Tier 3 approach were based on original (Orig) as well as adapted (Adap) estimates of *in situ* rumen degradation characteristics as model inputs) (see 3.4 for further explanation)

	Slaughter age (months)											
	14		20		24		30		36		44	
DMI (kg dry matter d^{-1})	9.7		10.6		8.9		9.2		6.9		7.4	
ADG (kg live weight d^{-1})	1.4		0.7		0.7		0.5		0.4		0.3	
Carcass yield (% of live weight)	55.0		55.0		55.0		55.0		54.0		53.0	
Carcass weight (kg)	262.0		272.0		291.0		299.0		291.0		285.0	
	Orig	Adap	Orig	Adap	Orig	Adap	Orig	Adap	Orig	Adap	Orig	Adap
CH_4 emissions												
$kg_{Tier\ 2}$ from cumulated DMI	35.2	-	79.0	-	87.7	-	131.8	-	124.1	-	167.7	-
$kg_{Tier\ 2}$ kg ADG^{-1}	0.15	-	0.31	-	0.27	-	0.38	-	0.34	-	0.48	-
$kg_{Tier\ 2}$ kg of $carcass^{-1}$	0.13	-	0.29	-	0.30	-	0.44	-	0.43	-	0.62	-
$kg_{Tier\ 3}$ from cumulated DMI	31.3	31.3	80.4	65.0	87.6	74.0	135.4	107.0	120.7	98.3	173. 9	145.0
$kg_{Tier\ 3}$ kg ADG^{-1}	0.13	0.13	0.32	0.25	0.27	0.23	0.39	0.31	0.33	0.27	0.47	0.40
$kg_{Tier\ 3}$ kg of $carcass^{-1}$	0.12	0.12	0.30	0.24	0.30	0.25	0.45	0.36	0.41	0.34	0.61	0.51

4.2 Comparison Methane Estimation between Tier 2 and Tier 3 Approaches

Improving the diet quality with feed supplements in beef cattle resulted in a decreased CH_4 emission. Very similar effects were estimated by the Tier 2 and Tier 3 (Adap) approaches (Figures 1 and 2). For the most extensive system M44WPS, the highest amounts of CH_4 were 168 and 145 kg CH_4 per animal slaughtered as estimated by the Tier 2 and Tier 3 (Adap) approaches, respectively (Figures 1 and 2). Also, predicted effects of energy and protein supplementation were similar (see results in previous section). The system with the shortest period until slaughter, M14TMR, emitted the lowest total amount of CH_4 with 35 and 31 kg CH_4 per kg cumulated DMI^{-1} with the Tier 2 and Tier 3 (Adap) approaches, respectively (Figures 1 and 2).

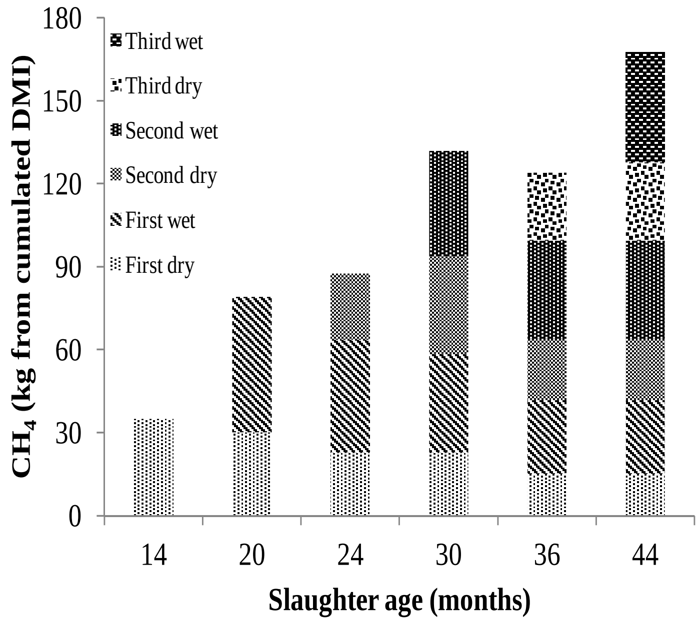

Figure 1 - Methane emission (kg CH_4 from cumulated DMI) estimated according to the IPCC Tier 2 approach for six systems reflecting variation in Brazilian beef production.

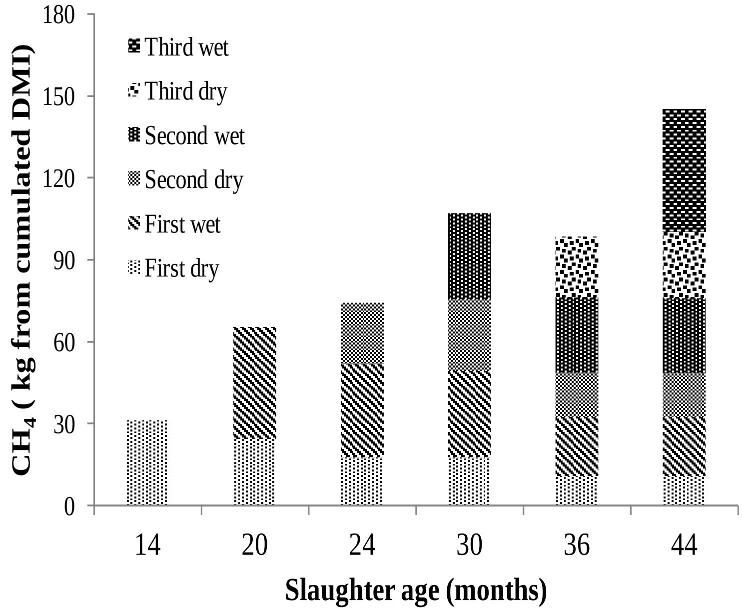

Figure 2 - Methane emission (kg CH_4 from cumulated DMI) estimated according to the IPCC Tier 3 approach (BANNINK et al., 2011) for six systems reflecting variation in Brazilian beef production. Calculations were performed with adapted estimates of rumen degradation characteristics (Adap; see 3.4 for further explanation)

Compared to estimated cumulative CH_4 emission per animal at slaughter when using the Tier 2 approach, the estimations with the Tier 3 (Adap) approach were on average 16% lower for all six systems (ranging from -11% to -20%). The predicted total tract digestibility of DM that was adopted in the Tier 2 approach, which is considered realistic according to Brazilian inventories, was utilized by the Tier 3 approach after adapting the *in situ* degradation characteristics for forage (Table 4; Tier 3, Adap). Although estimated CH_4 emission before the adaptation of estimates of *in situ* degradation characteristics for forage (Table 4; Tier 3, Orig) were more comparable to those than the Tier 2 approach (on average -1%; ranging from -11% to +4%), they were obtained with a substantially higher predicted total tract digestibility (on average for all seasons 15, 16, 15, 12, and 13 % units higher for M20WPS, M24TMR, M30WPS, M36TMR and M44WPS, respectively) than the values that are considered to be realistic (Table 6).

4.3 Methane Conversion Factor, Ym

With the original, uncorrected estimates of *in situ* degradation characteristics for forage, the Tier 3 (Orig) approach predicted a much higher diet digestibility (see results previous section), and the estimated Ym values were on average very similar to the Tier 2 default of 0.065 (0.064; lower during dry seasons, higher during wet seasons; Table 7). Correction of the *in situ* degradation characteristics for forage with the Tier 3 (Adap) approach resulted in Ym estimates that were increased by 7% and 13% for pasture finishing and feedlot-finishing systems, respectively. The Ym estimates were affected by the feed supplementation strategy. The higher the quantities of supplements that were offered, the lower the estimated Ym values were. Estimated Ym was on average, for all seasons and production systems, 20% lower (0.052) than the 0.065 default in the Tier 2 approach (Table 7).

Table 7 - The CH_4 conversion factor (Ym) based on the fraction of GEI emitted as CH_4 energy, when estimated with the Tier 3 approach for six Brazilian beef cattle systems differing in slaughter age and supplemental feeding strategy. With the Tier 3 approach, estimations are according to original (Orig) estimates of *in situ* degradation characteristics of forage as well as adapted (Adap) estimates of model inputs (see 3.4 for further explanation). With the Tier 2 approach, a constant fraction of 0.065 was assumed

	Slaughter age (months)											
	14		20		24		30		36		44	
	Orig	Adap	Orig	Adap	Orig	Adap	Orig	Adap	Orig	Adap	Orig	Adap
First dry	0.058	0.058	0.067	0.050	0.061	0.048	0.061	0.047	0.060	0.044	0.060	0.044
First wet		-	0.068	0.053	0.068	0.053	0.069	0.052	0.070	0.052	0.070	0.052
Second dry		-		-	0.062	0.062	0.063	0.046	0.063	0.045	0.063	0.045
Second wet		-		-		-	0.068	0.052	0.070	0.052	0.070	0.052
Third dry		-		-		-		-	0.059	0.059	0.056	0.047
Third wet		-		-		-		-		-	0.066	0.051

5 DISCUSSION

5.1 Mitigating Methane Emission by Enhancing Diet Quality and Animal Productivity

Increasing the proportion of concentrates in the diet results in an increased DMI and CH_4 emission per day, but reduces the duration of the growth period and the cumulative DMI for this period. The model estimations indicate this leads to a decreased cumulative CH_4 production from weaning till slaughter, which corresponds with the finding that CH_4 production in ruminants is strongly related to DMI and growth period (MOLANO; CLARK, 2008). In addition to a decrease in CH_4 production with a lower cumulative DMI and a shorter period between weaning and slaughter, an increased concentrate intake less CH_4 emission per kg DMI via an increased rumen passage rate and a reduced ruminal pH. These effects cause a fraction of starch and protein to bypass rumen fermentation, which flow undegraded into the intestine, and a more propionate-oriented type of fermentation, thus leading to a decrease in CH_4 from rumen fermentation (BENCHAAR et al., 2001). The present calculations with the Tier 2 and Tier 3 (Adap) approaches with feedlot-finishing demonstrate a 253% and 216% greater cumulative CH_4 emission level per animal slaughtered, respectively, for M36TMR when compared to M14TMR. For pasture-finishing, a 112% and 123% greater cumulative CH_4 emission level, respectively, was obtained for M44WPS when compared to M20WPS. These results indicate a profound decrease in the amount of rumen fermented feed required per unit of weight gain that is achieved in beef cattle under Brazilian conditions, thus demonstrating a high mitigation potential for diet supplementation, as it contributes to reduced enteric CH_4 emission per unit of beef product (GILL et al., 2010). The kg CH_4 per kg ADG as estimated by Tier 2 and Tier 3, respectively, when supplementing protein (M30WPS) was 79% and 74% lower when compared to no supplementation (M44WPS). Beef cattle reach slaughter weights faster because of the protein supplementation, which thereby lowered total lifetime CH_4 emission. Similar to the results of the present study, thus indicating the mitigation potential of a TMR diet under feedlot conditions during finishing instead of pasture feeding. Doreau et al. (2011) showed that CH_4 emission per kg of BW for beef cattle that were fed low grain diets were 56% greater than for beef cattle that were fed high grain diets during the fattening phase. In the present study (Table 6), on average, a 58% greater CH_4 emission per kg ADG was calculated for pasture-finishing systems (M20WPS, M30WPS, M44WPS) when compared to feedlot-finishing systems (M14TMR, M24TMR, M36TMR).

Different supplementation strategies are followed during the wet and dry seasons (Tables 1 and 2). A supplementation strategy during the dry season for a protein deficient diet is to feed supplemental protein sources in order to improve diet digestibility and diet utilization by cattle. The limiting DM digestibility and voluntary intake, due to a high cell wall and low crude protein content in forage, limits animal productivity. Fiber degradation in the rumen and microbial protein synthesis might be impaired by the low CP supply. DeRamus et al. (2003) reported that for protein supplementation with intensive grazing management, the overall efficiency of beef production increased and CH_4 emission per unit of beef product decreased. In contrast to the dry season, during the wet season, tropical grasses are not deficient in CP. Nevertheless, they still have low digestible energy content, and a relatively low fraction of organic matter is available for microbial degradation in the rumen and microbial protein synthesis. Therefore, supplementing energy to the rumen can be an effective way to deliver extra protein to the animal, due to an increase in microbial protein synthesis (POPPI; MCLENNAN, 1995). Despite the apparent high potential benefit of increasing animal productivity in developing countries by supplementing low quality diets, this requires an analysis of cost-effectiveness (WAGHORN; HEGARTY, 2011) because diet supplementation may prove to be a costly and long term process, and it may require genetic improvements in addition to improved nutritional practices.

In general, an increase in animal productivity is a very successful strategy for mitigating GHG emissions from ruminant systems in developing countries (FAO, 2013). In the present study, it was estimated that CH_4 emission per kg of carcass at slaughter varied by 123% between the beef production systems that were evaluated. Likewise, the CH_4 emitted by dairy cattle that was calculated according to the Tier 3 approach used in the inventory of GHG emissions in The Netherlands indicated that the 34% increase in annual milk yield per cow from 1990 till 2008 was accompanied by a 17% increase in CH_4 emission per cow, which led to 13% less CH_4 emitted per kg milk (BANNINK et al., 2011). In particular, in developing countries, animal productivity is generally low, mainly as a result of diet quality and local production conditions, and a higher number of animals and longer production cycles are required in order for animals to reach an acceptable carcass weight. However, an improvement in animal productivity in these countries will have profound effects on CH_4 emission.

In projections of the development of the Brazilian beef herd, Barioni et al. (2007) reported an expected rise in total enteric CH_4 emission in Brazil of 2.9% from 2007 to 2025. They considered this rise to be relatively low given the much greater expected increase in herd size of 7.4% and in beef meat production of 25.4%. The highest CH_4 emission of the most extensive system that was investigated in the present study can be explained by the low forage quality and availability, which are insufficient to meet the animals' requirements, thereby resulting in periodical weight losses that substantially increase the total life cycle until slaughter. This result is in agreement with Thornton and Herrero (2010), who calculated that 1,958 kg of CH_4 were emitted per ton of meat produced on natural grasslands (Cerrado vegetation) in an extensive production system in Central America, as compared to 395 kg of CH_4 in an improved production system, when daily grain supplementation is increased from 0.5 to 2.0 kg.

5.2 Methane Conversion (Ym) According to IPCC Tier 2 and Tier 3 Approaches

The original estimates of *in situ* rumen degradation characteristics as an input for the Tier 3 approach (Table 4; Tier 3, Orig) resulted in Ym estimations close to the fixed value of 0.065, which was adopted by the Tier 2 approach. However, these original estimates resulted in an unrealistically high diet digestibility. For a non-biased comparison between the Tier 2 and Tier 3 approaches, diet digestibility should be similar. Adapting the *in situ* rumen degradation characteristics (Table 4; Tier 3, Adap) was accompanied by an, on average, 20% lower estimated Ym value when compared to the Tier 2 value of 0.065. This indicates that the adoption of 0.065 with the Tier 2 approach may overestimate CH_4 emission in beef cattle kept under tropical conditions with a low pasture quality, such as tested for Brazilian conditions in the present study.

The Tier 2 approach only differentiates between diets that contain more than 90% concentrate and other diets by assuming a Ym value of 0.030 and 0.065, respectively, irrespective of feed intake level, chemical composition of the diet, and diet digestibility. However, these factors are known to affect enteric CH_4 production (BEAUCHEMIN et al., 2008). Although Ellis et al. (2010) demonstrated that the Ym factor model used by the Tier 2 approach performs adequately when compared with other tested empirical equations, they also argued that the concept of a fixed Ym of 0.065 does not have the capacity to describe changes in the composition of the diet and has limited use when estimating the impact of varying nutritional strategies on CH_4 emission. More recently, a similar conclusion was drawn from an extensive literature review by Hristov et al. (2013). In agreement with this, Kebreab et al. (2008) demonstrated that mechanistic models were better than empirical models in predicting CH_4 emission from US dairy cattle on feedlot systems with various feeding conditions. Nonetheless, the Tier 3 model performed worse when tested on the beef cattle data. Results showed a tendency for the Tier 3 model when compared to the Tier 2 model to over-predict CH_4 emission with a CCC value of 0.160 and a RMSPE value of 53.6% of the observed mean. This might be explained by error associated with estimating model inputs, or by an erroneous representation of fermentation processes in the case of beef cattle (BANNINK et al., 2011). In particular, the representation of volatile fatty acid production may not apply to beef cattle, as this was only derived from lactation cow data instead of beef cattle (BANNINK et al., 2006).

The results of the present study demonstrate the differences in the Tier 2 and Tier 3 approaches, and that a generic, fixed Ym value is unlikely to be applicable. Nevertheless, the present results with the Tier 3 approach need be considered with caution, as the model was developed and evaluated for dairy cattle and may be biased for beef cattle, as was already demonstrated by Kebreab et al. (2008) for intensive feeding systems. Despite the need for further development of the Tier 3 approach, it has the advantage of accommodating variations in Ym with feeding conditions, and hence may be used to generate country or system specific Ym values based on the logicality of known principles of rumen function and fermentative biochemistry. Results obtained in the present study support the idea that deriving more specific Ym values is required, which may improve CH_4 estimation substantially. Also, for the evaluation of the effectiveness of mitigation measures, such accuracy is a prerequisite (KEBREAB et al., 2008; ELLIS et al., 2008). A limitation of the use of mechanistic models is the complexity of these models, as is the necessity to have details available on diet composition and *in situ* rumen degradation characteristics (BANNINK et al., 2011). Nevertheless, it can be argued that the inputs that are required for the far more complex model representation with the Tier 3 approach are also relevant (and are hence required) for the Tier 2 approach.

5.3 Diet Supplementation to Mitigate Methane and GHG Trade-Offs

Improving diet quality with feed supplements results in an increased efficiency of beef cattle production and reduced CH_4 emission per unit of beef that is produced. Despite the high need to mitigate enteric CH_4, the net effect on GHG emissions may be far smaller when there are serious trade-offs towards other GHG sources. The impact of growing grains that are used for feed supplementation on GHG emissions must also be taken into account. Grain production gives rise to GHG such as N_2O emissions due to nitrogen fertilization of the crop, and CO_2 emissions as a result of soil preparation, harvest, and transport. Similar considerations apply to feedlot animal production (COTTLE et al., 2011). Nevertheless, accurate predictions of the response of enteric CH_4 emission to nutritional measures is needed still to be able to compare enteric CH_4 emission and GHG trade-offs in a reliable manner, and to estimate the effects of dietary changes in beef production systems on GHG emissions. The present study had a limited aim to contribute to an improved estimation of enteric CH_4 emission in Brazilian beef cattle.

6 CONCLUSION

Studying six types of beef systems representative of the variation encountered in Brazilian practice, differences in intensity of enteric CH_4 emission were quantified using a modelling approach. Model calculations indicate that going from a system without supplementation to a feedlot system (no grass forage) improves diet quality to such an extent that a three to fourfold decrease in CH_4 emission is obtained from cumulated DMI until slaughter, and per kg of ADG and per kg of carcass. Protein and energy supplementation of diets improves diet digestibility, increases daily weight gain, and reduces lifetime and age-at-slaughter with a major impact on CH_4 emission In current Brazilian inventory, a Tier 2 approach is applied to estimate enteric CH_4 emission based on a fixed default CH4 conversion factor of 0.065. With the Tier 3 approach, adapted to ensure similar diet digestibility as adopted with the Tier 2 approach, CH_4 the predicted CH_4 conversion factor was on average across seasons and production systems 20% lower (ranging from 5% to 32% lower) than the Tier 2 default. This results indicates that there is scope for alternatives to the Tier 2 approach to quantify enteric CH_4 emission and to come to a refinement of CH_4 conversion factors dependent on production conditions.

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