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Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use

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ABSTRACT

Brazil has the largest herd of beef cattle in the world, estimated at approximately 200 million animals. Production is predominantly pasture-based and low input and hence time to slaughter is long, which promotes high methane (CH_4) emissions per kg of product. The objective of this study was to investigate the impact of increasing animal productivity using fertilizers, forage legumes, supplements and concentrates, on the emissions of greenhouse gases (GHGs) in five scenarios for beef production in Brazil. A life cycle analysis (LCA) approach, from birth of calves to mature animals ready for slaughter at the farm gate, was utilized using Tier 2 methodologies of the IPCC and the results expressed in equivalents of carbon dioxide (CO_2eq) per kg of carcass produced. Fossil CO_2 emitted in the production of supplements, feeds and fertilizers was included using standard LCA techniques. The first four scenarios were based solely on cattle production on pasture, ranging from degraded *Brachiaria* pastures, through to a mixed legume/*Brachiaria* pasture and improved N-fertilized pastures of Guinea grass (*Panicum maximum*). Scenario 5 was the most intensive and was also based on an N-fertilized Guinea grass pasture, but with a 75-day finishing period in confinement with total mixed ration (TMR). Across the scenarios from 1 to 5 the increase in digestibility promoted a reduction in the forage intake per unit of animal weight gain and a concomitant reduction in CH_4 emissions. For the estimation of nitrous oxide (N_2O) emissions from animal excreta, emission factors from a study in the Cerrado region were utilized which postulated lower emission from dung than from urine and much lower emissions in the long dry season in this region. The greatest impact of intensification of the beef production systems was a 7-fold reduction of the area necessary for production from 320 to 45 m^2/kg carcass. Carcass production increased from 43 to 65 Mg per herd across the scenarios from 1 to 5, and total emissions per kg carcass were estimated to be reduced from 58.3 to 29.4 kg CO_2eq/kg carcass. Even though animal weight gain was lower in the mixed grass-legume scenario (3) than for the N-fertilized Guinea grass pastures (scenarios 4 and 5) GHG emissions per kg carcass were similar as the legume N_2 fixation input had no fossil-fuel cost. A large source of uncertainty for the construction of such LCAs was the lack of data for enteric CH_4 emissions from cattle grazing tropical forages.

1. Introduction

The recent report from the Brazilian government (MCTI, 2013) showed a reduction of 76% in greenhouse gas (GHG) emissions from the land use change and forestry (LULUCF) sector from 2005 to 2010, which was mainly attributable to the decrease in deforestation in Amazonia. In 2005, the LULUCF sector constituted 57% of all of Brazil's anthropogenic GHG emissions and with this decrease in deforestation, the total national emissions fell by 38% from 2032 Tg to 1247 Tg carbon dioxide equivalents (CO_2eq) in 2010. One consequence of this is that the agricultural sector, which represented 20% of all emissions in 2005, in the 2010 inventory now constitutes more than 35% of all emissions, of which over half (56%) are estimated to come from enteric methane (CH_4) and a further 18% from direct and indirect emissions of nitrous oxide (N_2O) from animal excreta deposited on pastures.

Over 94% of cattle in Brazil are raised for beef production and intensification is thought to lead to a reduction in the time to slaughter, pasture area and GHG emissions per kg of product (Berndt and Tomkins, 2013). According to the most recent statistics, 90% of beef cattle are raised and finished on pasture (ANUALPEC, 2015; Pedreira et al., 2015). In tropical regions, most production is on unfertilized pastures of grasses of African origin, mainly *Brachiaria* spp. Large responses in animal live weight gain (LWG) can be obtained with applications of

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nitrogen (N) and phosphorus (P) fertilizer or with the introduction of forage legumes (Euclides Filho et al., 2002; Andrade et al., 2012). The manufacture of fertilizers, especially N, requires significant fossil fuel inputs and hence increases the overall GHG emissions of the production systems. However, it can be expected that these emissions will be more than compensated for by the reduction in the time taken to fatten the cattle, such that there will be an overall reduction in GHG emissions per kg product (Thornton and Herrero, 2010; Crosson et al., 2011). The same may also apply to the extra N_2O emissions resulting from N fertilizer additions and those emissions related to feed and supplement production. Supplying N via N_2-fixing legumes instead of applying N fertilizer eliminates entirely the fossil CO_2 emissions associated with fertilizer manufacture and N_2O emissions from legumes may be lower than from N-fertilized swards (Jensen et al., 2012).

Attention has been given by some authors to the potential of *Brachiaria* pastures to accumulate soil carbon (Bustamante et al., 2012; Assad et al., 2013) and the evidence indicates that more productive pastures will accumulate more soil C than degraded pastures (Braz et al., 2013). This sink for atmospheric CO_2 is finite, site dependent, and will asymptotically approach a new steady state after some years (Johnston et al., 2009). As we feel that there are insufficient data available at present to allocate factors of CO_2 mitigation to this phenomenon in the different scenarios, it is not considered in this study.

The objective of this study was to investigate the impact of increasing pasture productivity using fertilizers, forage legumes, supplements and concentrates, on the emissions of GHGs per kg of product in 5 different scenarios using published emission factors (EFs) from the Intergovernmental Panel on Climate Change (IPCC) and available Brazilian data.

2. Material and methods

2.1. Estimation of GHG emissions

Within the overall strategy for this study a life cycle analysis (LCA) approach was adopted, covering the full cycle of the whole herd from birth of the calves to mature animals ready for slaughter at the farm gate. However, unlike full LCA studies where all environmental impacts of activities are evaluated, in this study only GHG emissions were accounted for. The GHG emissions were expressed as a function of the unit mass (kg) of carcass weight. This kind of analysis is often known as a “carbon footprint”.

The comparison of the GHG emissions from each scenario was made using Tier 2 methodologies of the IPCC (2006) and for fossil CO_2 used in the production process standard life cycle analyses. The basic data on herd composition, animal characteristics and performance and pasture productivity were sourced from the available Brazilian literature. The GHGs accounted for were:

a. CH_4 from enteric fermentation and from cattle dung;
b. N_2O emissions from dung and urine deposited in the pasture or in confinement sheds and N_2O from fertilizer applications in the field; and
c. GHGs (principally fossil CO_2) emitted in the production, manufacture and transport of animal feeds, fuels, fertilizers, pesticides and other agrochemicals and in the manufacture of the equipment and machinery used in the production systems.

The GHG emissions from the construction of farm buildings and machinery and the production of veterinary products and pesticides were not included in the study. This was the case for other GHG life cycle studies on Brazilian beef as it is assumed that such emissions are almost insignificant (Cederberg et al., 2009; Evans and Williams, 2009; Dick et al., 2015; Ruviaro et al., 2015). For the same reason in this and other studies, emissions associated with production of seeds were not accounted for.

To compare each of the 5 scenarios (Table 1) on an equal basis, the emissions were calculated from herds based on 400 reproducing females in each case with 16 bulls (Table 3), which is typical herd for the Cerrado region (Euclides Filho, 2000). The basic information on the animal performance indicators for each scenario, displayed in Table 2, was taken from a wide range of Brazilian literature, which is cited in the footnotes to this Table. These data include digestibility of the acquired forage in the different phases of animal growth, characteristics and fertility indices of the cows in the herd, carcass yields and weights. The numbers and carcass weights of each category of animals slaughtered (replaced cows, and finisher males and females) are listed in Table 4.

Total GHG emissions were estimated in CO_2eq using the global warming potential (GWP) conversion factors of 25 and 298 for CH_4 and N_2O, respectively (Forster et al., 2007) and the results expressed as CO_2eq per kg carcass weight (CW) which is equivalent to a fraction of between 0.48 and 0.54 of total animal live weight at slaughter (see Supplementary Information – SS01).

For full transparency the calculations of all emissions and ancillary data are presented in the spreadsheet SS01 provided in the Supplementary Information.

2.1.1. Enteric CH_4 emissions

Enteric CH_4 emissions were calculated using the standard IPCC Tier 2 methodology based on gross energy requirements and digestible energy in feeds (IPCC, 2006). This methodology requires the live weight of adult male and female animals, and the LW and daily LWG of all other categories of younger animals as displayed in Tables 2 and 3. In addition, the digestibility and protein content of the consumed forage/ration is required (Table 2). Using the procedures described in the IPCC manual (Chapter 10, IPCC, 2006) the total gross energy of each category of animal was calculated and it was assumed that the proportion of the gross energy intake converted into CH_4 (the Ym value) was 6.5% for all scenarios except for the finishing stage of scenario 5 when the cattle were receiving concentrate and the Ym was assumed to be 3% (Johnson and Johnson, 1995). The total CH_4 production of the whole herd was calculated using the proportion of days in the year that each animal category was in the field or feedlot, the number of each category of animals that subsequently yielded the total annual CH_4 production of the herd (Table 3).

2.1.2. CH_4 emissions from dung

The CH_4 emissions from the dung were determined from the total fecal production from the estimated forage intake and the digestibility. Forage intake (dry matter— DM) of each category of animal was calculated from the metabolic weight of the animal ($LW^{0.75}$) and the digestibility of the consumed forage. The values for digestibility used in the different scenarios are displayed in Table 2 and the live weights of each category of animal in Table 3. We used the equation 10.23 from the methodology (IPCC, 2006) to calculate the CH_4 emissions factor from dung and equation 10.24 to calculate volatile solids (VS) production for equation 10.24. This is fully described in the Supplementary information Spreadsheet SS1.

2.1.3. N_2O emissions from bovine excreta

For the estimation of N_2O emissions from dung and urine, firstly the total N intake was calculated from the protein content (6.25 × N concentration) of the forage/ration (Table 2) and from the DM intake, calculated as for the estimation of CH_4 emissions from dung. The total N excreted was assumed to be the N intake minus N accumulated in the animal carcass (2.5% of LWG – Scholefield et al., 1991) and N exported in milk in the case of lactating cows. Recently some estimates have been made of N_2O emissions from dung and urine in Brazil. As the majority of beef production in Brazil is on poorly managed pastures (as in scenarios 1 and 2), the protein content in the acquired diet is low and the proportion of N deposited in the dung can often be equal to or

Table 1
Details of the five scenarios of increasing intensity for beef production in Brazil.

Variable	Scenario 01	Scenario 02	Scenario 03	Scenario 04	Scenario 05
Pastures	*Brachiaria* sp.	*B. brizantha*	Mixed grass legume	Guinea grass	Guinea grass
Pasture management	No pasture reform. No lime or fertilizers added. Stocking rate 0.5 LU[1]/ha	Pasture reformed every 10 years. Lime (10 Mg/ha) every 10 year. Stocking rate 1.0 LU/ha	Pasture reformed every 5 years. Lime (10 Mg) every 5 years. Fertilized P[2] and K[2]. Stocking rate 1.7 LU/ha	Pasture reformed every 5 years. Lime (10 Mg) every 5 years. Fertilized N[3], P[2] and K[2]. Stocking rate 2.5 LU/ha	Pasture reformed every 5 years Lime (10 Mg) every 5 years. Fertilized N[3], P[2] and K[2]. Stocking rate 2.75 LU/ha
Breed of bovine	Undefined – crossreeds of *Bos indicus* and some blood of *Bos taurus*	Mixed breed Nellore with Gir, Guzera, Holsteins, Curraleiro, and other *Bos taurus*.	Nellore or Nellore crossbreeds. Predominantly blood of Nellore	Nellore or Nellore crosses – Best Nellore crosses	Nellore or Nellore crosses- Best Nellore crosses
Effect of breed	First calving late High mortality. Animal slaughtered between 3 and 4 year Meat low quality	Standard Nellore characteristics. First calving at 3 year. See Table 2.	First calving 2 year, more calves per cow, less mortality, animal finished early and higher carcass yield. See Table 2.	First calving 2 year, more calves per cow, less mortality, animal finished early and higher carcass yield. See Table 2.	First calving 2 year, more calves per cow, less mortality, animal finished early and higher carcass yield. See Table 2.
Diet in calving phase	Pasture forage only	Pasture forage with occasional mineral supplements	Pasture forage with mineral supplements	Pasture forage with mineral supplements	Pasture forage with mineral supplements
Diet in rearing phase	Pasture forage only	Pasture forage with occasional mineral supplements	Pasture forage with mineral supplements	Rotational grazing. Pasture forage with mineral supplements	Rotational grazing. Pasture forage with mineral supplements
Diet in finishing phase	Pasture forage only	Pasture forage with occasional mineral supplements	Pasture forage with mineral and energetic supplements	Rotational grazing. Pasture forage with mineral, protein and energetic supplements	Confinement with total mixed ration (TMR)[5].
Animal management[4]	Minimal, random animal breeding and only compulsory vaccines	Basic, with random animal breeding, only compulsory vaccines	Breeding season, controlled weaning, control of endo and ecto-parasites	Breeding season, controlled weaning, control of endo and ecto-parasites	Breeding season, controlled weaning, control of endo and ecto-parasites.
Performance documentation	Minimal	Management indicators	Individual animal identification, calving numbers and dates. Live weight gain.	Individual animal identification, calving numbers and dates. Live weight gain.	Individual animal identification, calving numbers and dates. Live weight gain related to specific grazing area.

[1] LU = 450 kg live weight.
[2] P and K fertilizers added according to soil analysis and standard recommendations.
[3] N added as urea at 3 times during the rainy season.
[4] With the exception of scenarios 4 and 5 (rearing phase) all grazing management was continuous.
[5] TMR composition (% DM) – silage 40, soybean 7, maize 50 urea 1 Lime 1.

greater than that in urine (Boddey et al., 2004; Xavier et al., 2014). For this reason Lessa et al. (2014) and Sordi et al. (2014) recommended the use of separate EFs for dung and urine, and the study of Lessa et al. (2014) showed that for the Cerrado region the EFs were far lower in the dry season (5 mo) than in the rainy season. The ratio of N excreted in urine and in dung were calculated using the equation of Scholefield et al. (1991):

$$R_{u/f} = [1.2725 * (\%N \text{ in diet})] - 1.09 \quad (1)$$

Where $R_{u/f}$ is the ratio of N excreted in urine to that in dung.

The direct N_2O EFs adopted for urine and dung in the 7 month rainy season were 0.0193 (1.93%) and 0.0014 (0.14%), respectively, and 0.0001 (0.01%) and zero for urine and dung in the dry season. The justification for the use of these EFs is considered in more detail in the Discussion section.

To estimate the emissions of N_2O from dung and urine during the 75-day finishing stage (confinement) in scenario 5, the default emission factor recommended in Chapter 10 (Tables 10.21 of the IPCC manual and 10.22 for direct and indirect N_2O emissions, respectively, IPCC, 2006) was applied for a "dry lot" system.

2.1.4. Fossil CO_2 emissions in resources utilized

The fuel and energy and the fertilizers and feeds utilized in the beef production systems are listed in Table 5. The GHG emissions from these inputs were accounted for using IPCC factors for the materials where possible and other sources identified and cited in the literature. Mineral salt was assumed to be 60% $CaCO_3$ and 40% $Ca_3(PO_4)_2$ and the fossil energy used (CO_2eq) in their manufacture was taken from Table 3 of West and Marland (2002). The fossil fuel requirement for the maize and soybean in the supplements and silage were taken from an updated version of de Barros Soares et al. (2009) using inputs and yields for these crops under typical management for the Cerrado region. The N_2O emissions from the N fertilizer and the N deposited as residues in the production of these crops was also accounted for (See supplementary information, folders E1 and E2, Spreadsheet SS01). These crops are generally produced under no-till, with no N fertilizer for soybean and in this case 96 kg N fertilizer for maize with yields of 2900 kg ha^{-1} for soybean and 5200 kg ha^{-1} maize (means for Brazil in 2014 – LSPA-IBGE, 2015).

The emissions of CO_2eq associated with electrical energy and diesel fuel (for quantities see Table 5) were calculated using the factors 3.53 kg CO_2eq/L diesel fuel (74.1 kgCO2eq/GJ - IPCC, 2006) and 115 kg CO_2eq/MWh for electricity (EPE, 2015). The mean value for GHG emissions for electricity generation in Brazil is low as 71% of generation is from hydropower, and 11.3, 7.6, 4.4, 2.4, 2.6% and 1.1%, respectively, from natural gas, biomass, petroleum derivatives, nuclear, coal and wind (data for 2013 – EPE, 2015).

2.2. The scenarios

Approximately half of the beef cattle herd and planted pastures in Brazil are located in the central-west savanna region known as the Cerrado (IBGE, 2008). For this reason, in this study to evaluate the impact of intensification of beef production on GHG emissions, we used the edaphoclimatic conditions of this area as a backdrop for the study. Details of the history of the clearing of the Cerrado for the introduction of pasture, and subsequently cropping, have been given by Boddey et al. (2003). The present investigation was based on five different scenarios for beef production of increasing intensity, all existing practices, but adopted to widely different degrees (Table 1). Scenarios 1 through to 4 represent 90% of beef production – all raised solely on pasture, scenario 5 with a 75-day finishing period on total mixed ration is an option that is slowly increasing and is the most intensive scenario possible in

Table 2
Indicators of animal performance for the five scenarios of beef production.

	Scenario 01	Scenario 02	Scenario 03	Scenario 04	Scenario 05
Annual mean digestibility of the acquired diet in each production phase (%)					
Calving phase	49[1]	56[2]	60[3]	63[4]	63[4]
Rearing phase	49[1]	56[2]	60[3]	63[4]	63[4]
Finishing phase	49[1]	56[2]	60[3]	63[4]	70%[5]
% Crude protein in dry matter intake	7[1]	8[1]	10[1]	10[1] and 11[1]	10[1] and 13[6]
Characteristics of the cows[7]					
Milk production (kg per day)	3.1	3.7	3.7	3.7	3.7
Lactation period (months)	7	7	7	7	7
Age at the first calving (months)	36	30	30	30	30
Live birth rate (%)[8]	55	60	70	70	70
Annual pregnancy[9] rate (%)	60	65	75	75	75
Replacement rate reproducing females (%)	15	15	12.5	12.5	10
Ratio bull/female	1/25	1/25	1/25	1/25	1/25
Animal mortality (%)[8,9,10]					
Mortality up to 1 year	7	5	5	5	5
Mortality from 1 to 2 years	2	2	2	2	2
Mortality from 2 to 3 years	2	1	1	1	1
Mortality after 3 years	1	1	1	1	1
Carcass characteristics[11]					
Weight of male carcass	230	240	250	250	265
Weight of female carcass	200	210	220	220	235
Male carcass yield (%)	50	51	52	52	54
Female carcass yield (%)	48	50	50	50	52
Animal weights[12]					
Adult cows (kg)	430	430	430	430	430
Adult bulls (kg)	650	650	650	650	650
Weight at birth (kg)	30	32	35	35	35
Weight at weaning male (kg)	160	170	185	185	185
Weight at weaning female (kg)	140	155	170	170	170
Weight at start of finishing male(kg)	380	380	380	380	380
Weight at start of finishing female(kg)	360	360	360	360	360
Live weight gain (LWG) rearing phase male (kg d^{-1})[13]	0.25	0.30	0.38[9]	0.40	0.40
(LWG) rearing phase female (kg d^{-1})[13]	0.20	0.24	0.30	0.32	0.32
LWG finishing phase male (kg d^{-1})[14]	0.40	0.60	0.75[15]	0.90	1.50
LWG finishing phase female(kg d^{-1})[14]	0.32	0.48	0.60	0.72	1.20

[1] Means of estimates for unfertilized *Brachiaria* swards from Pereira et al. (2009), Euclides et al. (2009), Macedo et al. (2010), Xavier et al. (2014).
[2] Means of estimates for well managed *Brachiaria* swards but without N fertilizer with from Euclides et al. (2009).
[3] Based on a diet of 50% *Stylosanthes* sp. (cv. Campo Grande) and 50% *Brachiaria brizantha* (Embrapa, 2007; da Silva et al., 2013).
[4] Gerdes et al. (2000) and De Quadros and de Rodrigues (2006).
[5] Based on 25% of roughage and 75% concentrate (Millen et al., 2009; Ferraretto et al., 2012).
[6] % crude protein in confinement diet.
[7] Euclides Filho et al. (1995).
[8] Number of life births from 100 cows. This number includes rates of pregnancy, abortion and dead births.
[9] Corrêa et al. (2001).
[10] Bertazzo et al. (2004).
[11] Rosa et al. (2001).
[12] ANUALPEC/FNP (2008).
[13] Mean annual LWG which includes a 5 to 6 month dry season with low weight gains typical of the Cerrado region.
[14] These weight gains are higher as all finishing on pastures is conducted in the rainy season.
[15] According to Vilela and Ayarza (2002) and Embrapa (2007) the introduction of forage legumes increases LWG by an average of 25%.

the edaphoclimatic conditions of the Cerrado region without the introduction of integrated crop livestock systems.

Predicted diet characteristics, typical stocking rates and indicators of animal performance for each scenario were taken from the Brazilian literature (Table 2). From these data the number of the different categories of cattle and their live weights and rates of gain in live weight were computed using the methodology of Granger and Walsh (1959) and are displayed in Table 3 (see also folder B2 of the Spreadsheet Supplementary data SS01). The stocking rates are expressed in livestock units (LU) which in Brazil is defined as a live weight of 450 kg.

2.2.1. Scenario 1

Degraded *Brachiaria* pasture: Pastures of *Brachiaria* were introduced into the Cerrado region starting in the 1970s and the specie *B. decumbens* (cv. Basilisk) was the most planted. The native vegetation was cleared, the soil limed and fertilized for the planting of a grain crop, usually rice, and the *Brachiaria* was planted immediately afterwards to take advantage of the residual nutrients. Considerable areas of these pastures still exist and have, in many cases, never received any fertilizers since establishment. In this scenario, animal management is minimal with no documentation or monitoring of animal performance, no provision of mineral salt lick, and no control over animal breeding. It was assumed that these pastures were never renewed. In these more extensive scenarios (1 and 2) the average cow will produce its first calves only after 3 years, and lose fertility after 10 years, the cows have a useful reproductive life of only 7 year or less. Annual pregnancy rate was assumed to be 55% in Scenario 1 and 60% in Scenario 2 (Table 2). It is a tradition on these farms to replace 15% of the cows with young adult females every year.

2.2.2. Scenario 2

In the late 1980s there was a serious problem with spittle bug attack (*Deois* spp.) on *B. decumbens*. Embrapa launched a variety of *B. brizantha* (cv. Marandú) tolerant to this insect and within a few years this grass

Table 3
Description of animal categories, number and duration in each phase (category) for each scenario.

Animal category	Number	Starting and end weight (kg)	Duration (d)
Scenario 1			
Bulls	16	650	365
Cows	400	430	365
Male calve	110	30–160	210
Female calve	110	30–140	210
Male young	103	160–270	440
Female young	102	140–250	440
Male 3 years old	100	270–380	275
Female 3 years old	100	250–360	367
Male finisher steers	100	380–460	200
Female finisher heifers[1]	100	360–417	189
Total head	1041[2]		
Scenario 2			
Bulls	16	650	365
Cows	400	430	365
Male calve	120	32–170	210
Female calve	120	32–155	210
Male young	114	170–380	700
Female young	114	155–360	683
Male finisher steers	114	380–471	151
Female finisher heifers[1]	114	360–420	130
Total head	884[2]		
Scenario 3			
Bulls	16	650	365
Cows	400	430	365
Male calve	140	35–185	210
Female calve	140	35–170	210
Male young	133	185–380	513
Female young	133	170–360	500
Male finisher steers	133	380–481	134
Female finisher heifers[3]	133	360–440	133
Total head	962[2]		
Scenario 4			
Bulls	16	650	365
Cows	400	430	365
Male calve	140	35–185	210
Female calve	140	35–170	210
Male young	133	185–380	488
Female young	133	170–360	475
Male finisher steers	133	380–481	112
Female finisher heifers[3]	133	360–440	111
Total head	962[2]		
Scenario 5			
Bulls	16	650	365
Cows	400	430	365
Male calve	140	35–185	210
Female calve	140	35–170	210
Male young	133	185–380	488
Female young	133	170–360	475
Male finisher steers	133	380–491	74
Female finisher heifers[4]	133	360–452	74
Total head	962[2]		

[1] A 15% replacement rate was used for these scenarios (60 young adult females).
[2] The number of head considers the animals present in the herd in one year. Young animals change to finishers during the year and are thus counted only once.
[3] A 12.5% replacement rate was used for these scenarios (50 young adult females).
[4] A 10% replacement rate was used for this scenario (40 young adult females).

became widely planted. In this scenario, we assume that the pasture is *B. brizantha*, that there is some documentation of the animals, mineral salts are provided, at least sporadically, but there is no control over animal breeding. It was assumed that the pasture was renewed every 10 year by plowing and liming (1 Mg ha^{-1}) but with no other fertilizers (Sparovek et al., 2007). For the scenarios 2 through to 5 the tillage operations for the pasture renewal were considered to use a medium size tractor with a fuel consumption (diesel oil) of 13.4 L/h for 2.5 h for each ha (Sá et al., 2013). The replacement rate for producing females in this scenario was also 15%.

2.2.3. Scenario 3

Evidence shows that the most limiting nutrient to grass growth in this region is N, followed by P (e.g. Oliveira et al., 2001). The introduction of a forage legume such as *Stylosanthes* spp. or forage groundnut (*Arachis pintoi*) into these pastures has been shown to be very effective in increasing pasture yields and animal weight gains (Vilela and Ayarza, 2002; Andrade et al., 2012) although adoption has been poor, as very careful management is required for the legume to persist in the sward. The great advantage of the legume is the complete elimination of the GHG emissions (fossil CO_2 from natural gas) associated with the manufacture and application of N fertilizer (Robertson and Grace, 2004) and possibly lower N_2O emissions. In this scenario lime was added at 1 Mg ha^{-1} and P and potassium (K) fertilizers are added at planting and the legume chosen was *Stylosanthes* spp. (cv. Campo Grande) which is that most adopted in the Cerrado region (Embrapa, 2007). Breeding is managed within a specific season, weaning is controlled. Animals carry individual identification and dates of calving are registered. LWG is monitored at regular intervals and there is control of endo and ecto-parasites. It was assumed that the pasture was renewed every 5 year by plowing and liming (1 Mg ha^{-1}) and with the addition of 100 kg P and 100 kg K ha^{-1}. For this more productive scenario cows start calving at 2 years, and the replacement rate was assumed to be 12.5%.

2.2.4. Scenario 4

This scenario also relies on animals reared entirely on pastures, but in this case of Guinea grass (*Panicum maximum*) cv Tanzânia, which was developed at the beef cattle center of Embrapa (Campo Grande, MS) and has found widespread adoption among those who wish to apply significant N and other fertilizers. In this scenario, lime and P and K fertilizers are added at planting and N fertilizer (urea) is added three times during the rainy season at 50 kg N ha^{-1} at each application. Breeding is controlled as for scenario 3 as is animal identification, LWG

Table 4
Category slaughtered per year, carcass weight and total carcass weight at slaughter.

Category	Number of cattle	Carcass weight (kg)	Total (kg)
Scenario 1			
Cows[1]	56	206.4	11558
Finisher female	40	200.0	8051
Finisher male	100	230.0	23058
Total			42668
Scenario 2			
Cows[1]	56	215.0	12040
Finisher female	54	210.0	11340
Finisher male	114	240.0	27360
Total			50740
Scenario 3			
Cows[2]	46	215.0	9890
Finisher female	83	220.0	18260
Finisher male	133	250.0	33250
Total			61400
Scenario 4			
Cows[2]	46	215.0	9890
Finisher female	83	220.0	18260
Finisher male	133	250.0	33250
Total			61400
Scenario 5			
Cows[3]	36	223.6	8050
Finisher female	93	235.0	21855
Finisher male	133	265.0	35245
Total			65150

[1] Refers to replaced cows = 15% replacement (60 young adult cows) minus 1% annual mortality (4 cows).
[2] Refers to replaced cows = 12.5% replacement (50 young adult cows) minus 1% annual mortality (4 cows).
[3] Refers to replaced cows = 10% replacement (40 young adult cows) minus 1% annual mortality (4 cows).

and other data registration and parasite control. It was assumed that the pasture was renewed every 5 year by plowing and liming (1 Mg ha^{-1}) and with the addition of 100 kg P and 100 kg K fertilizer ha^{-1}. The replacement rate again was assumed to be 12.5%.

2.2.5. Scenario 5

In this case management at the calving and rearing stage are on fertilized Guinea grass pastures with the same management as in scenario 4 with renewal every 5 years, but at the finishing stage (75 days) the animals are confined and fed with total mixed ration (TMR - for composition see footnote 5, Table 1). Breeding is controlled as for scenario 3 as is animal identification, LWG and other data registration and parasite control. Replacement rate in this scenario was reduced to 10%.

According to the most recent statistics (ANUALPEC, 2015) 11.2% of beef cattle are finished (fattened for slaughter) in confinement (the equivalent of our scenario 5) and a further 7% are finished on "intensively managed pastures" (scenario 4). The number of ranchers using mixed legume pastures (scenario 3) is very small (>1.0%) such that it can be assumed that approximately 82% of beef cattle are raised and fattened on *Brachiaria* pastures (scenarios 1 and 2).

3. Results

3.1. Land use and carcass yield

Total annual carcass yield (Table 6) was calculated from the number of cattle slaughtered per year and carcass weight, data derived from Tables 2, 3 and 4. For the scenarios 1 and 2, where no energetic supplements or mixed ration were used, the area occupied by the herd was based only on the stocking rates and the herd size (Table 6). The recovery of degraded pastures (scenario 1 - stocking rate 0.5 LU/ha) and replanting with *B. brizantha*, scenario 2 - stocking rate 1.0 LU/ha) even without any N fertilizer or the introduction of a forage legume, were estimated to reduce the area occupied by the herd by over 50%. Further large reductions in area are attained by fertilization of the pastures and the introduction of a forage legume or the application of N fertilizer. Whereas the area needed for grazing decreases with intensification through to the final scenario (5), in this scenario it was estimated that 27 ha of land would be required under Brazilian conditions to produce the required amount of TMR (104 Mg/herd/year) and silage (210 Mg/herd/year – Table 5) such that there was only a 9% reduction in area required for the herd in scenario 5 compared to scenario 4.

As carcass yield per herd per year also increased with intensification, there was a very large, over seven fold, increase in the carcass yield per ha through the increasingly intensive management from scenarios 1 to 5 (Table 6).

Table 5
Annual consumption of typical inputs per herd.

Inputs	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Mineral salt (kg)	–	12400	26809	26809	53618
Supplements (kg)[1]	–	–	28818	40339	103992
Maize silage (kg)	–	–	–	–	210350
Electric energy (MWh)	19667	19667	19667	19667	78670
Diesel tractor (l)	–	2276	2895	1968	3579
Lime (kg)[2]	–	67947	86410	58759	53417
P fertilizer (kg)[2]	–	–	8641	5876	5342
K fertilizer (kg)[2]	–	–	8641	5876	5342
Urea (kg)[2]	–	–	–	44069	40063

[1] Maize and soybean. For GHG emissions associated with the production of supplements and silage see On-line Spread-sheet (SS1) folders E1 and E2.
[2] Does not include lime and fertilizers used on maize and soybean crops for supplements/silage — see On-line Spread-sheet (SS1) folders E1 and E2.

3.2. Methane emissions

Enteric CH_4 is produced as a function of total energy in the ingested diet. The IPCC Tier 2 methodology estimates gross energy intake of all different categories in the herd, and accounts not only for animal LW but also for the extra energy needed for grazing, growth (LWG), and for females, pregnancy and milk production (see Supplementary information SS1 folder F3). In the scenarios with improved forage and supplements the rates of LWG were higher and the quantity of digestible feed necessary for this improved rate of LWG was higher. However, the total annual dry matter intake (expressed as 'Gross Energy intake') decreased as pasture quality was improved from scenario 1 through to scenario 4 for two reasons: a) the digestibility of the forage improved and hence the total DM intake necessary to provide the same amount of digestible energy decreased, and b) in scenarios 1 and 2 an extra energy requirement of 36% was established for "net energy for maintenance" for "grazing of large areas" (Table 10.5 – IPCC, 2006) compared to 17% for normal grazing for scenarios 3, 4 and 5. For the last 75 days of scenario 5 this value for extra energy was 0% as the animals were fed in confinement. As under Tier 2 enteric CH_4 emission is directly proportional to total energy (DM) intake, the annual CH_4 emission decreased from scenario 1 through to 4 for all types of animal (even for those not gaining weight such as the bulls) and total enteric and dung CH_4 emissions per herd decreased by 46% from scenario 1 to 4 and by 50% for scenario 5 (Table 7).

The Tier 2 methodology predicts large increases in enteric CH_4 emissions per head with decrease in the digestibility of the acquired diet. However, as the total carcass production increased by 50% from scenario 1 through to scenario 5 the estimates indicated that there was a 67% decrease in CH_4 emissions per kg product (Table 7).

3.3. Nitrous oxide emissions

According to the equation published by Scholefield et al. (1991) the ratio of urine N to fecal N depends on the N content of the grazed forage and for scenarios 1 and 2 the prediction was that the proportion of N excreted in urine was, respectively, 25 and 35% and for scenario 3, 4 and 5, 49% (See Supplementary information SS1 — Folder F3). The only occasion when the N deposited in urine was estimated to be higher than that in dung was in the finishing (feedlot) phase of scenario 5 when the cattle were fed TMR (13% protein or 2.1% N) and it was estimated that 61% of the excreted N was in the form of urine (Table 8).

As there are no data available for N_2O emissions from N fertilizer applied to tropical pastures in Brazil, the default Tier 1 EF of 0.01 for N fertilizer (1% of fertilizer was assumed to be emitted as N in the form of N_2O) was used and accordingly the estimates of the N_2O emissions from the 150 kg N ha^{-1} added to the pastures had a very large impact on total N_2O. For the scenarios 1 and 2, where no N fertilizer was added and the urine-N to dung-N ratio was very low, the estimates of indirect emissions were higher than those for direct emissions. The estimation of indirect N_2O EFs is fraught with difficulties and they are derived mainly from estimates of N leaching and volatilization. N leaching in the rainy season, from urine patches especially, could be very significant, although the results of Lessa et al. (2014) contradict this for their study in the Cerrado region. As rainfall is so scarce in the 5-month dry season, leaching losses at this time must be negligible. Dry season losses through N volatilization from urine patches could easily exceed the 20% estimate used to calculate the indirect EF for this indirect emission. We do not have enough data to justify the use of any EFs other than those cited by IPCC (2006) for Tier 1 for these indirect emissions, but for the less intensive systems where dung N predominates, it is likely that indirect EFs are considerably lower than for systems that are more intensive.

IPCC (2006 - Chapter 11. p 11.16) states that N_2O emissions from "The nitrogen residue from perennial forage crops is only accounted for during periodic pasture renewal, i.e. not necessarily on an annual

Table 6
Total area occupied by, and carcass production of, each herd for each scenario. Including cropped area for supplemental feeds and total mixed ration.

Scenario	Livestock unit (LU)[1]	Stocking rate (LU/ha)	Grassland (ha)[2]	Cropland (ha)	Total (ha)	Carcass weight (kg)	kg carcass per ha	Area per kg carcass (m^2)
1	683	0.5	1365.8	–	1365.8	42,667.6	31.2	320.10
2	679	1.0	679.5	–	679.5	50,740.0	74.7	133.91
3	734	1.7	432.1	5.80	437.8	61,400.0	140.2	71.31
4	734	2.5	293.8	10.69	304.5	61,400.0	201.7	49.59
5	734	2.75	267.1	27.22	294.3	65,149.6	221.4	45.17

[1] 1 livestock unit (LU) = 450 kg live weight.

basis as is the case with annual crops." For scenario 1 where there is no pasture renewal there is thus no emission to be computed. With *Brachiaria* pastures not fertilized with N, apart from urine and dung patches (already accounted for above), emissions have been found to be extremely low (Neill et al., 1995; Wick et al., 2005; Lessa et al., 2014). For the *Stylosanthes*/*Brachiaria* mixed sward there are no data available for emissions from residues, and we have addressed this issue in the Discussion.

3.4. Fossil carbon dioxide emissions

On ranches/farms principally dedicated to pasture-based beef production, fossil energy inputs are mainly derived from the energy necessary to manufacture and distribute fertilizers and, to a lesser extent, mineral salt for animal consumption. On arable farms diesel oil consumption for mechanical operations is often very considerable (see Supplementary Information SS1, folder F1), but for pasture-based beef production the main diesel fuel consumption was for disking and harrowing at the time of pasture renewal (Table 5).

Electricity consumption was estimated based on da Silva (2006) who gave a value of 14.4 kWh/ha/year. For the largest ranch (scenario 1) this would result in a consumption of 24.8 MWh/year or an emission of 2.3 Mg CO_2/year (Table 9). We assumed that for scenarios 2, 3 and 4, electricity consumption would be the same even though pasture areas were was considerably less (reduced by 50, 68 and 78% for scenario 2, 3 and 4, respectively). For scenario 5 the more intensive confinement stage would consume more electrical energy and we assume this could be four times as much as for the other scenarios. The impact of including these estimates of electricity on total fossil CO_2 emissions is very small ranging from 0.14 to 0.05 kg CO_2/kg CW.

The largest contributions of fossil CO_2 were derived from applications of lime and fertilizers. As neither were applied in scenario 1, total fossil CO_2 emissions are extremely low (Table 9). Lime neutralizes soil acidity and releases CO_2, at a rate of 0.476 kg CO_2/kg lime according to IPCC (2006). A low rate of lime (100 kg ha/year or 1 Mg every 10 years) was proposed for scenario 2, but as the grazed area was 680 ha, the associated fossil CO_2 emission was only 21% lower than for scenario 3, and 14% and 21% higher than for scenarios 4 and 5, respectively, where 200 kg lime/ha/year (1 Mg every 5 years at renewal) were added on 294 ha, or 267 ha, of grazed pasture, respectively. For the mixed legume/grass pasture scenario (3), only P and K fertilizers were applied (100 kg P and 100 kg K/ha at each renewal) and the fossil CO_2 emissions associated with their production was estimated as 0.54 kg CO_2/kg CW/year based on the values of 2.70 and 1.11 kg CO_2eq/kg P and K respectively (Ledgard et al., 2011). However, N fertilizer has a higher fossil energy cost (3.88 kg CO_2eq/kg urea N – Ledgard et al., 2011) and was applied in scenarios 4 and 5 at rates far higher (150 kg N/ha/year) than for P and K, such that the impact on fossil CO_2 emissions was much greater, 3.2 and 2.7 kg CO_2/kg CW for these two scenarios, respectively.

The other fossil CO_2 emissions originated from mineral salt (scenarios 2 through 5 – Table 9) and from the supplements and TMR (scenarios 3 through 5). The calculation of fossil emissions to produce the maize and sorghum supplements and ration are displayed in the supplementary information (Spreadsheet SS1, folders E1 and E2).

3.5. Total GHG emissions

The total emissions showed a decrease from scenario 1 through to 3, principally due to the decrease in methane emissions promoted by the decrease in total DM intake. But for the scenarios where N fertilizer was applied to the pastures (scenarios 4 and 5) the large increase in fossil CO_2 and N_2O emissions derived from the manufacture and application of the N fertilizer led to an increase in total emissions per herd compared to the scenario 3 with the mixed grass/legume pasture.

The "carbon footprints" in CO_2eq per kg CW are displayed in Fig. 1. From the degraded pasture scenario (1) through to the mixed grass/legume pasture (scenario 3) there was a 50% decrease in the carbon footprint (CF) due principally to the decrease in CH_4 emissions/kg CW. Methane emissions decreased somewhat further with improvement of pasture quality in scenarios 4 and 5, but the CO_2 emissions derived from the manufacture and application of N fertilizer and the N_2O emissions from this source both increased such that the total CF increased in scenario 4 and the most intensive scenario (5) with final fattening with confined animals showed emissions almost exactly the same as for the mixed grass/legume pasture (scenario 3).

4. Discussion

Two studies have been published which specifically address the question of the total Life Cycle production of GHGs in the production (the CF) of Brazilian beef. The studies were designed to produce a value for the CF of beef produced in Brazil for export to Sweden (Cederberg et al., 2009) and to Britain (Evans and Williams, 2009).

Table 7
Estimates of annual emissions of CH_4 by each herd in each scenario using Tier 2 methodology of the IPCC.

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
	kg CH4	%	kg CH4	%	kg CH4	%	kg CH4	%	kg CH4	%
Bulls	2091.5	2.2	1659.1	2.2	1280.7	2.1	1099.2	2.1	1099.2	2.3
Cows	41832.2	43.6	33784.7	44.4	27170.7	44.4	23318.9	45.3	23318.9	48.7
Calves	5865.0	6.1	5248.0	6.9	5222.2	8.5	4399.1	8.6	4399.1	9.2
Young animals	31614.4	33.0	25209.8	33.1	18385.4	30.1	15047.4	29.3	15047.4	31.4
Finishers	12245.8	12.8	8695.3	11.4	7949.7	13.0	6618.9	12.9	3150.9	6.6
Dung	2187.8	2.3	1520.9	2.0	1133.9	1.9	952.4	1.9	901.5	1.9
Total	**95836.6**		**76117.8**		**61142.6**		**51435.9**		**47916.9**	
kg CH_4/kg carcass	**2.25**		**1.50**		**1.00**		**0.84**		**0.74**	
CO_2 eq/kg carcass	**51.66**		**34.50**		**22.90**		**19.27**		**16.92**	

Table 8
Estimates of annual nitrous oxide emissions in kg per herd or per kg of produced carcass calculated using the Tier 2 methodology of the IPCC.

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
	Direct	Indirect	Direct	Indirect	Direct	Indirect	Direct	Indirect	Direct	Indirect
Bulls	4.4	5.4	6.6	6.3	11.2	8.1	11.5	8.3	11.5	8.3
Cows	68.2	84.1	104.5	99.0	183.3	131.7	188.3	135.3	188.3	135.3
Calves	2.8	3.5	6.6	6.6	18.1	13.4	18.5	13.7	18.5	13.7
Young cattle	41.3	50.8	89.1	76.2	124.0	86.7	118.6	83.3	118.6	83.4
Finishers	15.2	18.8	20.1	20.5	40.0	30.1	32.8	24.8	97.2	16.4
N fertilizer							692.5	225.1	629.6	204.6
Total (kg)	131.9	162.5	227.0	208.7	376.6	270.0	1062.3	490.5	1063.7	461.6
Total (kg)	**294.4**		**435.7**		**646.6**		**1552.8**		**1525.4**	
kg N_2O/kg carcass	0.0069		0.0086		0.0105		0.0253		0.0235	
CO_2 eq/kg carcass	**2.06**		**2.56**		**3.14**		**7.54**		**7.00**	

The Swedish study concentrates heavily on the possible impacts of GHG emissions of expansion of the area under beef production into the Amazon region, this being a potential driver for deforestation and extremely large GHG emissions. The authors calculate on the basis of national data collected from IBGE (2008) and ANUALPEC/FNP (2008) that 175 m^2 of pasture is needed to produce 1 kg of CW (Cederberg et al., 2009). This is far higher than our estimate of 74.7 m^2 for scenario 2, the scenario which might be considered to be close to the "average" for Brazil (Table 6).

These authors used Tier 1 methodology to estimate GHG emissions but appear to have used a simplified herd composition. A typical beef-cattle farm in Brazil does not separate the different phases of animal production such as calf production ("cria"), growth phase ("recria") and finishing ("terminação"), but the whole cycle is usually conducted on one property. In our study, for an all-pasture system (scenarios 1 through 4) approximately 800–1000 animals in the herd produce between 48 and 76 Mg of CW over periods of 38 and 26 months. The herd composition used by Cederberg et al. (2009) was not clearly described, but both the CH_4 and N_2O emissions were calculated based on Tier 1 methodology and were, respectively, 21.6 and 6.3 kg CO_2eq/kg CW. These values were 23 and 38% lower than our Tier 1 estimates (see Supplementary information SS1 — Folder F2) for scenario 2. This suggests that they used a somewhat lower ratio of herd size/weight to carcass yield compared to that used in our study for this scenario. The estimate of Cederberg et al. (2009) of fossil CO_2 emissions (0.30 kg CO_2eq/kg CW) was lower than ours (0.88 kg CO_2eq/kg CW) as we assumed that 10 Mg of lime was added every 10 years in scenario 2, which was not considered in their study. Their final value for total emissions (CF) was 28.2 kg CO_2eq/kg CW, compared to ours of 40.9 kg CO_2eq/kg CW for scenario 2.

As in our study, the British study gave a clear account of herd composition based on 400 reproducing females (Tables A5-2 to A5-5, Evans and Williams, 2009) and gave an annual carcass yield per herd of 59.5 Mg considerably above our estimate of 51.4 Mg for scenario 2, but very close to the 61.1 Mg for scenario 3. The total emission for 1 kg CW was given as 31.7 kg CO_2eq compared to our estimate of 29.6 kg CO_2eq for scenario 3 (Table 10), but in the available documentation no breakdown of this total into emissions of CH_4, N_2O and fossil CO_2 seems to be given.

Table 9
Annual emissions of CO_2 fossil (kg CO_2eq/herd) associated with consumables, feeds and fuels[1].

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Salt	0.0	2033.6	4396.7	4396.7	8793.3
Supplements and silage	0.0	0.0	8944.5	9888.3	36957.6
Electrical energy	2261.8	2261.8	2261.8	2261.8	9047.0
Diesel fuel	0.0	8035.0	10218.5	6948.6	12633.7
Lime	0.0	32342.6	41131.4	27969.3	25426.7
Fertilizers	0.0	0.0	32896.5	193358.6	175780.6
Total	**2261.8**	**44673,0**	**99849.1**	**244823.2**	**268638.9**
kg CO_2/kg carcass	**0.05**	**0.88**	**1.63**	**3.99**	**4.12**

[1] For inputs see Table 5 and for methods used to calculate emissions see Materials and methods Section.

Two other recent studies have estimated total GHG emissions for several scenarios for beef production in Brazil, but specifically for the Southern Region of Brazil in the State of Rio Grande do Sul. The study of Dick et al. (2015) examined two contrasting scenarios: A) Extensive system (ES) — beef-cattle free-grazing native pastures (often degraded) in the southern Pampas region of the state with no fertilizers applied to the sward nor salt lick for the animals and B) Intensive system (IS) — cattle grazed on native pastures in summer improved with the introduction of ryegrass, oat and the legumes clover and birdsfoot trefoil and grazed in a 7-day rotation. The study of Ruviaro et al. (2015) compared seven different scenarios for beef production with Aberdeen Angus cattle in the same region and most extensive scenario was very similar to the ES described above. The other six systems were of increasing intensity from improved natural grass through scenarios with rye grass, ryegrass and sorghum and with increasing allowances of salt and protein energy supplement. Both studies appear to have estimated enteric emissions of CH_4 and those from dung using the Tier 2 methodology exactly as described in this study (see Supplementary Information SS01). They calculated the total N excreted by the cattle from the total N intake then adopted the Tier 1 methodology for N_2O emissions which uses the same EF (0.02) for dung and for urine.

For the extensive system of beef production on unimproved native grasslands in both studies, fossil CO_2 inputs were extremely small, as was the case for our scenario 1. The results of the two studies give extremely different estimates of total GHG emissions per kg of product. Ruviaro et al. (2015) reported a carbon footprint (CF) per kg live weight of 42.6 kg CO_2eq (equivalent to 85.1 kg CO_2eq/kg CW in the units used

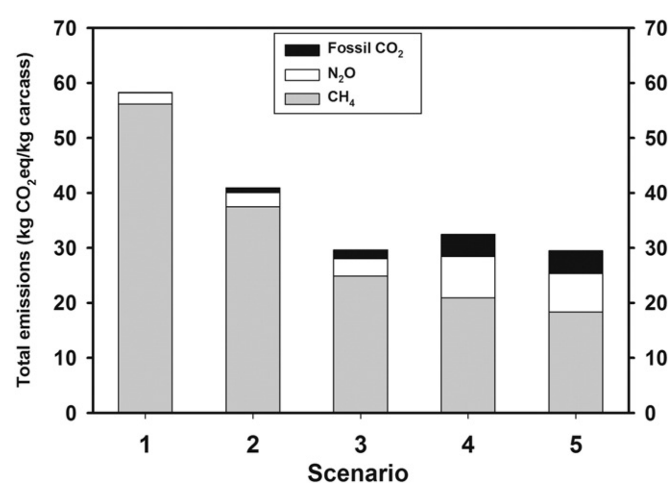

Fig. 1. Greenhouse gas emissions from five different scenarios for production of beef in Brazil estimates using Tier 2 methodology of the IPCC (2006). Data expressed as emissions in CO_2 equivalents per kg of carcass produced.

Table 10
Total annual emissions per herd of CH_4, N_2O and fossil CO_2 and the total of all three GHGs and the total emission per kg of produced carcass.

Scenario	CH_4	N_2O	CO_2	CO_2eq	Carbon footprint
	Mg herd^{-1}	kg herd^{-1}	Mg herd^{-1}	Mg herd^{-1}	kg CO_2eq kg carcass^{-1}
1	95.8	294	2.3	2486	58.3
2	76.1	436	44.7	2077	40.9
3	61.1	647	99.8	1821	29.6
4	51.4	1553	244.8	1993	32.4
5	47.9	1525	268.6	1921	29.4

in our study) and Dick et al. (2015) 22.5 kg CO_2eq/kg LW (equivalent to 45.0 kg CO_2eq/kg CW). Both studies explained clearly how CH_4 and N_2O emissions were calculated from the quantities and the digestibility and crude protein in the ingested diets. The digestibility and crude protein of the ingested diet were given as 45 and 8.3%, respectively, by Ruviaro et al. (2015) and 47 and 12% by Dick et al. (2015). The difference in crude protein content in the diets is considerable, but this parameter has no effect on the estimate of CH_4 emissions when Tier 1 or Tier 2 methodology are used, although there is a significant impact on estimates of N_2O emissions. As the values used for digestibility of the ingested diet were so similar it is difficult to account for the very large differences in the estimates of the CF of beef produced on this extensive grazing of native grassland.

The beef production system with the lowest CF studied by Ruviaro et al. (2015) was that based on cultivated ryegrass and sorghum (N fertilizer applied at 165 kg N/ha) with an estimate of 40.0 kg CO_2eq/kg CW, which was over twice as high as that for the intensive system studied by Dick et al. (2015) at 18.3 CO_2eq/kg CW. The authors of both studies seem to have followed in a very similar manner the IPCC (2006) Tier 2 and Tier 1 guidelines for calculating the CH_4 emissions from the cattle and dung and the N_2O emissions from dung and fertilizer, respectively. Both studies provide considerable information on herd composition, but not enough to discover differences that would account for estimates of emissions per kg CW between 90 and 119% higher in one study than in the other.

In our study in all scenarios the largest single GHG emission was enteric CH_4 (Fig. 1). This was especially true for the least intensive systems where for scenario 1, 96% of the total GHG emission was due to enteric CH_4 and even for the most intensive system (scenario 5), 61%. As was pointed out by Kurihara et al. (1999), very few data are available for enteric CH_4 emissions from cattle fed on tropical forages, and even less for actual free-grazing animals that would select a diet of different composition from those fed cut forage. These authors suggested that their data indicated that the “methane conversion ratio”, termed by the IPCC as ‘Ym’ (page 10.30 IPCC, 2006), could be considerably different from the standard value for forages of 6.5%. This could have a very large impact on estimates of total GHG emissions and the degree to which intensification is capable of mitigating these emissions. It is obvious that considering the global importance of beef production on tropical forages, especially that in Brazil, that there is an urgent need for studies on enteric CH_4 production as a function of intake for cattle grazing *Brachiaria* spp. and other tropical forages.

In ruminant production systems with animals grazing forage of low protein content the majority of excreted N is in the form of dung (Barrow and Lambourne, 1962; Scholefield et al., 1991). It is well documented that N_2O emissions from dung are considerably lower than from urine and hence a single EF applied to total excreted N is inappropriate (Flessa et al., 1996; Yamulki et al., 1998; Sordi et al., 2014). In order to integrate into the Tier 2 methodology, separate EFs for urine-N and dung-N, the equation developed from the data of Barrow and Lambourne (1962) which derives the ratio of urine-N to dung-N from the N concentration of the ingested diet was utilized. This equation was shown to closely fit measured data for diets based on *Brachiaria* sp. of low crude protein content by Macedo et al. (2010) and Xavier et al. (2014). Our recent study in the Cerrado region indicated that in the rainy season N_2O emissions were far lower in the dry season (5 mo) than in the rainy season (Lessa et al., 2014). Thus the direct N_2O EFs adopted for urine and dung in the 7 month rainy season were 0.0193 (1.93%) and 0.0014 (0.14%), respectively, and 0,0001 (0.01%) and zero for urine and dung in the dry season. The adoption of these EFs separated by form of excreta and season had a major impact on lowering the estimates of N_2O emissions from excreted N. When this methodology was utilized, compared to the use in Tier 1 of the standard EF of 0.02 for all excreted N (Supplementary information SS1 – Folder F2), the estimates of N_2O emissions from this source were reduced by a factor of 5.8 for scenario 1 and by approximately 2.6 for the scenarios 3 to 5.

Our study is based on five different beef production scenarios in the tropical Cerrado region of Brazil where approximately 50% of the beef cattle herd in the country is situated. The production systems are very different to those in Rio Grande do Sul. The cattle in the Cerrado region are principally Nellore, the pastures are formed with the tropical forage grasses *Brachiaria* spp., or *P. maximum*, and the region has a hot and rainy season which lasts from November to April followed by a cooler dry season which has very infrequent rainfall. The Tier 2 estimates for the different scenarios ranged from 58.3 kg CO_2eq/kg CW for the degraded pasture (scenario 1) to 29.4 kg CO_2eq/kg CW for the most intensive scenario (5).

In the review of Crosson et al. (2011) most whole-farm beef production systems described were considerably more intensive than those described in this study and most GHG emissions/kg CW were lower than even our more intensive scenarios (3, 4 and 5). Our highest N fertilizer rate of 150 kg N/ha is modest by standards use in the intensive dairy or beef production systems of Europe, North America, Australia or New Zealand. Further intensification of Brazilian pasture-based beef production systems in the tropical regions such as in the Cerrado, Amazonia and the north east, could be pursued by using higher fertilizer rates and more responsive grasses such as Tifton (*Cynodon dactylon*). However, higher animal productivity and lower emissions are unlikely to be realized, as the breeds of cattle (notably Nellore) which are able to resist the high temperatures, the humidity of the wet season and the insect- and tick-borne diseases of these regions, generally do not have the potential to transform the improved forage quality into much higher LWGs.

The legume proposed for introduction in the scenario 3 was *Stylosanthes* spp. which has been used with some success in the Cerrado region (Vilela and Ayarza, 2002; Embrapa, 2007). The input of biological N_2 fixation by such tropical legumes can exceed 100 kg/ha/year (Cadisch et al., 1989; Miranda et al., 1999; Boddey et al., 2015) but no studies on the possible significance of N_2O emissions from N-rich residues of tropical legumes are yet available. For this reason the N_2O emissions from this source were assume to be zero. If alternatively it is assumed that 100 kg N/ha/year is deposited on/in the soil as legume residues, as was reported for a mixed pasture of *B. humidicola*/*Desmodium ovalifolium* in the South of Bahia (Boddey et al., 2015), and the standard N_2O EF of 0.01 for crop residues is utilized (IPCC, 2006), this results in an annual N_2O emission of 1.57 kg N_2O/ha or 678 kg N_2O/herd (grazing 432 ha) or 3.3 kg CO_2eq/kg CW. This raises the CF for scenario 3 (the grass/legume pasture) to 32.9 kg CO_2eq/kg CW somewhat above the CF of the most intensive scenario (5 at 29.4 kg CO_2eq/kg CW) and comparable to the scenario with a fertilizer application of 150 kg N/ha (scenario 4 – Table 10 and Fig. 1).

5. Conclusions

It is clear from this and other published studies that the intensification of beef cattle production systems leads to a reduction in emissions of GHGs per unit of product, the so-called carbon footprint. We have attempted to maximize the transparency of the methodology used to produce the estimates of the CFs and we consider that the study has sufficient internal consistency to show that the change from extensively-grazed degraded pastures to grass-legume mixed swards or N-fertilized improved pastures reduces the CF by between one third to a half. Greater reductions may theoretically be possible if animals of higher performance were utilized, but few breeds except Nellore have the resistance to high temperatures and animal parasites (e.g. ticks and tick-borne parasites) that occur in the Cerrado region.

Comparisons of our study with other studies in Brazil or other parts of the world are hampered by a lack of detail and transparency in how the estimates of other studies were arrived at. The IPCC manuals (e.g. IPCC, 2006) give detailed methodologies to calculate emissions from ruminants of all types given all types of feed although some studies give little detail about how the methods were applied and the use of models, such as SimaPro (Goedkoop et al., 2008), can often hide the details of how results were arrived at. To calculate the CF it is necessary to apply the methods on a whole herd, and herd structure differs from region to region. Often few details are given and comparisons between regions and countries can only be very approximate.

The great advantage of intensification is not directly associated with the emissions of enteric CH_4, N_2O emissions from excreta or fossil CO_2 inputs in supplies and transport, but in the reduction in area required to produce the same quantity of product. According to our estimates the area required to produce one kg of carcass on a degraded pasture is approximately 320 m^2 but this falls to 45 to 50 m^2 for the two most intensive scenarios (4 and 5) even when the area to produce the crops necessary for supplements and feeds is counted. Even in scenario 3, the mixed grass/legume pasture, the area required to produce 1 kg CW falls to 71 m^2. One consequence of incentives by the government for farmers under the low carbon agricultural plan ("Programa ABC") to invest in intensification of beef production systems should be the reduction of pressure on the reserves of native vegetation. It is known that pasture improvement alone can increase soil carbon stocks (Braz et al., 2013), which is another motive for government investment in this area in the drive to lower GHG emissions in the agricultural sector.

In this study scenario (3) was based on the use of a N_2-fixing legume introduced into the pasture to increase the crude protein in the acquired diet. The N from this source comes with no carbon cost for manufacturing unlike the very considerable fossil input required for N fertilizer, but at present, the possible magnitude of N_2O emissions from legume residues is unknown. However, our simulation suggested that the CF will only be approximately 10% higher than that of the most intensive system (scenario 5). Final fattening under confinement at in scenario 5 has other major negative environmental impacts such as pollution of local water sources and foul odor derived from disposal of concentrated animal wastes.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.agsy.2015.12.007.

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