

Article

Mitigating Greenhouse Gas Emissions from Beef Cattle Production in Brazil through Animal Management

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Abstract: Beef cattle production is an important agricultural activity in Brazil, which influences environmental and resource consumption. This study analyzed greenhouse gas (GHG) emission impacts from 17 farms, representing the Brazil's productive system and determined possible improvements in the production chain. Methane, nitrous oxide, and carbon dioxide emissions were evaluated using the updated Intergovernmental Panel on Climate Change (IPCC) guidelines for national inventories. The GHG inventory included emissions from animals, feeds, and "cradle-to-farm-gate" operations for animal management. Regression analyses of carbon dioxide equivalent (CO₂eq) emissions and productive indices were performed to identify possible GHG emission hotspots. The results varied considerably among the farms. The GHG yield ranged from 8.63 to 50.88 CO₂eq kg carcass^{−1}. The productive indices of average daily gain ($p < 0.0001$), area productivity ($p = 0.058$), and slaughtering age ($p < 0.0001$) were positively correlated with GHG yield. However, no correlation was found with the stocking rate ($p = 0.21$). The production chain could be improved through accurate animal management strategies that reduce the slaughtering age and daily weight gain individually or per area using pasture management and strategic animal supplementation, which could subsequently reduce GHG emissions in beef cattle production.

Keywords: GHG emissions; livestock; sustainable intensification; beef production; GHG inventories



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1. Introduction

In an ever-changing world, with the increasing global demand for food, supplying food to the entire human population has become increasingly challenging [1,2]. By 2050, the global population is estimated to reach 12 billion, which will be accompanied by a decrease in world poverty and increase in food consumption in developing and underdeveloped countries. Highly populous Asian countries, such as China and India, will undergo a substantial increase in the consumption of animal proteins, particularly beef [3]. However, cattle feed production leads to natural resource consumption and can increase the emission of greenhouse gases (GHGs), such as nitrous oxide (N₂O), methane (CH₄), and carbon dioxide (CO₂). Therefore, natural ecosystems must be preserved simultaneously [4–6]. To overcome this challenge, production must be increased without affecting the environment.

In beef cattle production, CH₄ is emitted due to fiber fermentation in the rumen and feces decomposition in the soil [6,7]. Nitrous oxide is emitted from animal excreta and nitrogen fertilization [8,9], while CO₂ is generated from fossil fuels, energy, chemicals, materials, seeds, and transport [10,11]. From an environmental perspective, the carbon footprint (CF) is an indicator that facilitates the evaluation of the impact of a product, such as carcass production, in terms of global warming, because it assesses GHG emissions on the same basis, which is the carbon equivalent (CO₂eq) [4,10,12].

Brazil has the largest commercial population of beef cattle, and the GHG emissions from this sector account for approximately 17% of the total emissions in Brazil [13]. Therefore, strategies must be urgently developed to mitigate these emissions. A method to reduce the impact of ruminant production on global climate change is by increasing productivity by providing good quality feed, which can effectively reduce CH₄ emissions per unit of animal products [3,5,14]. In Brazil, the weaning rate, average daily weight gain per head, and slaughtering age are lower than those of tropical forage and animals potential [1,15,16].

Several strategies have been proven to increase the average daily gain (ADG) and gain per area. Dellevatti et al. (2019) showed that by using moderate N fertilization (180 kg N ha⁻¹ y⁻¹) in a Marandu grass pasture with a grazing target of 25 cm canopy height in a continuous grazing method, the ADG can be increased from 350 to 900 g animal⁻¹ d⁻¹ during the backgrounding phase of beef production [15]. Cezimbra et al. (2021) found that improving sward structure through adjustments in forage allowance resulted in greater forage intake and live weight (LW) gains in beef cattle [17]. Strategic supplementation has also increased the average gain [6], by focusing primarily on the utilization of non-human edible foods [2]. Most of the previous studies have focused on a specific mitigation strategy or on the life cycle of beef cattle production systems [4,17,18]. Pasture quality is one of the main factors affecting GHG emissions in pasture-based beef production systems [19]. Therefore, further investigation is required to identify management practices at the farm level which lead to reduced GHG emissions.

In this study, we developed a novel method to analyze the GHG emissions from real farming production systems. The objectives of this research were to survey the zootechnical indices of Brazilian livestock in different regions and management intensification practices, estimate the environmental impacts associated with different production farms, and identify strategies to reduce the environmental impacts of livestock production.

2. Materials and Methods

We used the yield scaled GHG inventory to assess the GHG impact of beef cattle production. The goal was to evaluate and compare the environmental impact in terms of CF from 17 productive farms, which comprise 300,000 heads (animals) and 220,000 hectares.

Herein, the farms were selected to obtain primary data according to the following criteria: (1) representativeness of Brazilian beef cattle production systems in terms of herd size, feeding strategy, and farm operations; and (2) existence of an organized accounting and management system that provides comprehensive and good-quality data for inventory analysis.

In particular, typical farming systems in Brazil use *Urochloa* grasses as the main source of feed in pasture, and the breed is Nellore and its crosses. The forage production and nutritive value of these grasses vary seasonally. In general, the animals are reared in an extensive pasture production system.

The farms considered in this study are located in the states of Espírito Santo, Goiás, Minas Gerais, Mato Grosso, Pará, Paraná, and Tocantins, which are responsible for over 70% of beef cattle production in Brazil. The farm sizes ranged from 250 to 100,000 ha, and the number of animals ranged from 450 to 80,000 (Table 1).

Table 1. Characteristics of evaluated farms.

Farm No.	Municipality	State	Operation	Area (ha)	Head
1	Prata	MG	Cow–Calf	1500	2000
2	Santa Vitória	MG	Full Cycle	800	667
3	Nanuque	ES	Backgrounding/Finishing	14,407	12,296
4	Barra Do Garça	MT	Backgrounding/Finishing	1524	2449
5	Redenção	PA	Backgrounding/Finishing	8811	9085
6	Palmas	TO	Backgrounding	13,558	16,134
7	Jundiá Do Sul	PR	Backgrounding/Finishing	2033	3291
9	Carneirinho	MG	Full Cycle	1700	6610
10	Araguaína	TO	Backgrounding/Finishing	20,000	22,000
11	Cássia	MG	Backgrounding	250	450
12	Cássia	MG	Backgrounding	600	1100
13	Campinápolis	MT	Backgrounding	2323	934
14	Figueirópolis D’oeste	MT	Full Cycle	16,000	35,000
15	Figueirópolis D’oeste	MT	Full Cycle	100,000	80,000
16	Alta Floresta	MT	Backgrounding	10,000	30,000
17	Jussara	GO	Backgrounding/Finishing	12,000	70,000

2.1. Functional Unit and Allocation

The production of 1 kg of LW from bullocks, heifers, replacement cows, and bulls at the farm gate levels was defined as the functional unit in our study. In food product-related studies, the economic allocation criteria are preferred [10]; the economic product in this study was kilograms of LW. We could not identify any alternative product system for the coproduct. In Brazil, beef cattle production is commercialized using the unit arroba (one unit equals 30 kg of LW, considering carcass yield). The price per kilogram of LW varies according to local and year–season production. In March 2021, 1 kg of LW was approximately equal to 2 American dollars.

The allocation factors do not include excess manure produced for use in crop production or in grassland fields, because biofertilizers and compost are not commonly produced in the evaluated farms.

2.2. System Boundaries

Cradle-to-farm-gate systems were used as boundary systems, by considering all farm operations of beef cattle production. Therefore, the study considered the direct impacts due to on-farm operations and the indirect impacts from the production and transport of synthetic fertilizers, diesel, electric energy, concentrates, and mineral salt.

The CO₂ from livestock respiration is not considered as a net source of global warming according to the Kyoto Protocol; therefore, we did not include this factor in the calculations. Soil carbon stock variation was not included in GHG estimations because it does not affect animal-related operations. Therefore, the system boundaries comprised the annual GHG emissions and beef cattle production (meat sold on an LW basis).

2.3. Emissions Inventory

Data for the productive indices and GHG emissions were collected from 17 Brazilian beef production systems for 2019 and 2020, during which production was ongoing. Only farms that had herds in steady-state conditions were considered. The modeling data were integrated with the reviewed literature and the electronic spreadsheet prepared by Cardoso et al. (2016) based on the IPCC models [4], which facilitated the calculation of GHG intensities.

2.4. Impact Assessment

The impacts on feed production and utilization for animal feeding included concentrates and silage. The use of these feeds varied among the farms and across seasons. Specific emission factors for 1 kg of silage and concentrate production, and emissions associated with the production and transport of fertilizers, concentrates, and mineral salts were adopted from Cardoso et al. (2016) [4]. Generally, silage is produced in each farm, and concentrates are brought from the local marketplace for use or mixed on the farm.

No irrigation was used in the farms, although electricity was used for water transportation, corrals, and other facilities. A Brazil-specific GHG emission factor ($0.227 \text{ kg CO}_2 \text{ kWh}^{-1}$) was considered to account for the electricity supplied to the farms [20].

The approach of IPCC (2019) Tier 2 was used to calculate both direct and indirect emissions from nitrogen fertilization used in the grassland [21]. The local emission factors measured by Cardoso et al. (2019) were used for direct nitrous oxide (N_2O) emissions, and N that was lost as ammonia was considered to be volatilized [8]. Direct N_2O emissions accounted for 1% of the total nitrogen fertilizer applied to the soil. The volatile fraction of the fertilizer was 15%. Indirect N_2O emissions were considered as 1% of the volatilized N. Leaching was not considered because it does not commonly occur in most Brazilian soils. Carbon dioxide emitted after fertilization was considered to be 0.2 kg per kilogram of applied urea [21]. Nitrous oxide from animal excreta was calculated from previous studies conducted in Brazil [8,22,23]. The direct N_2O emission factor was 0.63% of N excreted by the animals. The fraction of volatilized N was 12% [8,24]. Indirect N_2O emissions from excreted N were 1%. The total N consumed and excreted by animals was estimated using the BR Corte (2016) equations by Valadares Filho et al. [25], which is more reliable for Nellore and their crosses. The calculation methods for the emission factors are shown in Table 2.

Table 2. Emissions factors used for GHG inventory calculations.

Pollutant	Calculation	Emissions Factor
CH_4 Feces	Kilogram Per Head	$0.4 \text{ kg CH}_4 \text{ Head}^{-1} \text{ Y}^{-1}$
N_2O Direct	$\text{N}_2\text{O From Fertilizer} = \text{N Applied} \times \text{EF} \times 44/28$ $\text{N}_2\text{O From Excreta} = \text{N Excreted By The Animals} \times \text{EF} \times 44/28$	$\text{EF} = 0.01 \text{ kg N}_2\text{O-N}$ $\text{EF} = 0.0063 \text{ kg N}_2\text{O-N}$
N_2O Indirect	$\text{N}_2\text{O Indirect Volatilization From Fertilizer} = \text{N Applied} \times \text{EF} \times 44/28$ $\text{FRACfert} = 15\%$ $\text{N}_2\text{O Indirect Volatilization From Animal Excreta} = \text{Nexc} \times \text{EF} \times 44/28$ $\text{FRACexc} = 12\%$	$\text{EF} = 0.01 \text{ kg N Volatilized}$

Nexc, annual N from animal excretion; EF, emission factors; FRACfert, fraction of N applied volatilized; FRACexc, fraction of N excreted by the animals.

The methane calculations included enteric CH_4 from feces. A mean soil methane emission factor of $0.4 \text{ kg CH}_4 \text{ per head y}^{-1}$ was used based on national studies [8,22,23]. The IPCC Tier 2 approach was used to estimate enteric CH_4 based on gross energy requirements and the digestible energy of feed [21]. The gross energy (GE) intake was calculated using feed composition tables of all ingredients [25]. Thus, CH_4 production was calculated as the percentage of GE intake considering a CH_4 conversion factor (γ_m) of 6.5%. This emission factor is reliable because several Brazilian studies [6,7,26] have confirmed that the enteric CH_4 from animals bred in high-forage diets is similar to that recommended by the IPCC for national inventories.

The methodology developed by IPCC 2013 was used to assess the GHG impacts [27]. Global warming potentials across 100-year horizons were used to convert GHG emissions

into carbon dioxide equivalents (CO₂eq). The factors used for CO₂, fossil CH₄, biogenic CH₄, and N₂O were 1, 28, 25, and 265, respectively.

2.5. Data Analysis

Linear regression analysis was conducted among the productive indices of average daily weight gain, stocking rate, slaughter age, and animal productivity per area with the response variable, kg CO₂eq per kg LW produced, to identify variables that affected the variations in the GHG impacts for the studied systems.

3. Results and Discussion

The ADG was 0.436 kg animal d⁻¹, changing from 0.16 to 0.84 kg animal⁻¹ d⁻¹ (Table 3). GHG emission intensities reduced the increasing ADG and were highly correlated with individual animal gains ($p < 0.0001$; $r^2 = 0.65$). Therefore, strategies that improved ADG could contribute to mitigating GHG impacts. Several strategies were recently adopted to achieve the highest indices presented herein (~0.84 kg animal⁻¹ d⁻¹). One option is to maximize the short-term herbage intake rate by the bovines (g dry matter min⁻¹), which can be achieved through low-intensity grazing and high-frequency rotational stocking [17]. Nitrogen fertilization also ensured improved individual animal performance. For Marandu palisade grass, during the forage growing season, it is possible to obtain approximately 0.9 kg animal⁻¹ d⁻¹ during the backgrounding phase by applying 180 kg N three times per year, adjusting the stock rate to maintain a pasture height close to 25 cm in a continuous stocking grazing method [15]. These productivities were also obtained with strategic animal supplementation [6]. Integrated crop–livestock systems provide higher individual and per area animal production [16]. Legumes such as forage peanut (*Arachis pintoi*) are promising to obtain high ADG [28]. All these strategies promoted a higher green leaf allowance for grazing. Pasture quality is an important factor influencing GHG emissions in pasture-based beef production [19].

Table 3. Zootechnical indices and emission intensities from the studied farms.

Farm	Average Daily Gain (kg Animal ⁻¹ D ⁻¹)	Stocking Rate (AU Ha ⁻¹)	Productivity (kg Ha ⁻¹)	Slaughtering Age (Months)	Emission Intensity (kg CO ₂ Kg ⁻¹ LW ⁻¹)
1	0.160	1.26	102	51	50.9
2	0.247	0.68	80	40	35.2
3	0.348	0.68	113	38	21.4
4	0.414	0.86	243	32	14.6
5	0.291	1.09	128	45	35
6	0.558	0.83	218	24	15.7
7	0.521	0.70	226	22	12.8
8	0.284	1.19	168	46	29.2
9	0.521	3.70	799	24	19
10	0.510	0.84	213	26	16.1
11	0.273	0.92	179	42	21
12	0.601	1.26	418	19	12.4
13	0.410	0.49	120	28	16.8
14	0.375	1.56	311	26	20.6
15	0.241	0.53	73	41	30.1
16	0.839	2.50	1195	14	8.6
17	0.820	5.83	1937	16	12.4

1 AU = 450 body weight.

The average stocking rate was 1.47 AU ha⁻¹ and varied from 0.53 to 5.83 AU ha⁻¹ (Table 3). The average Brazilian national stocking rate is 1.1 AU ha⁻¹ and has doubled since 1990 [1]. A stocking rate potential of 6 AU ha⁻¹ in *Urochloa* grasslands can be achieved using fertilization alone or in combination with animal supplementation [15,15]. However, the stocking rate did not affect GHG emissions in this study ($p = 0.28$).

The average animal production per area was 384 kg LW ha⁻¹ y⁻¹ and ranged from 73 to 1937 kg y⁻¹ (Table 3). The Brazilian national production per area is 120 kg and has increased fourfold since 1990 [29]. If this annual rate is maintained, the average value obtained in this study would be achieved by 2030. The same strategies used for improving ADG resulted in greater production per area and reduced the emission intensity.

However, in Brazil, the number of calves per cow per year is approximately 60% less than that of important global beef cattle producers, such as the United States and Australia, with an annual rate of 90–95% [30]. Therefore, further research should focus on the effect of cow–calf operations and their impact on the CF of Brazilian beef cattle.

The average yield-scaled GHG emissions were 21.9 kg CO₂eq kg⁻¹ carcass, and varied from 8.6 to 50.9 kg CO₂eq kg⁻¹ carcass (Table 3). The system boundaries of the present and previous studies are not identical; therefore, difficulties may arise when comparing these types of studies. Our values are consistent with those calculated by Cardoso et al. (2016) [4] for different levels of intensification and those by Florindo et al. (2018) [18] for Brazilian Central-West productive systems [18]. However, our values were greater than those obtained for integrated crop–livestock systems [31]. Integrated crop–livestock systems are one of the most promising alternatives for reducing GHG impacts from beef cattle production in Brazil. However, the lack of specific emission factors for each gas makes it difficult to draw this conclusion definitively.

The contribution of each gas to the yield-scaled GHG emissions varied significantly among farms, at averages of 71%, 27%, and 2% for CH₄, N₂O, and CO₂, respectively. The contribution of CH₄ varied from 65% to 78%. Nitrous oxide ranged from 22% to 33%, and CO₂ ranged from 1% to 9% (Figure 1). Several studies have confirmed that a methane conversion factor of 6.5% of the GE intake is a reliable predictor of enteric CH₄ production in Brazil [1,6,7,26]. Therefore, to reduce CH₄ emissions, strategies such as increasing the ADG and decreasing the slaughtering age should be prioritized. The highest contribution of N₂O emissions was observed in farms that used N fertilization. However, N fertilization can increase carbon stocks [32]. The inclusion of legumes in grasslands can lead to increased forage production, animal gain, and increased carbon stocks, without generating an additional N₂O source [28].

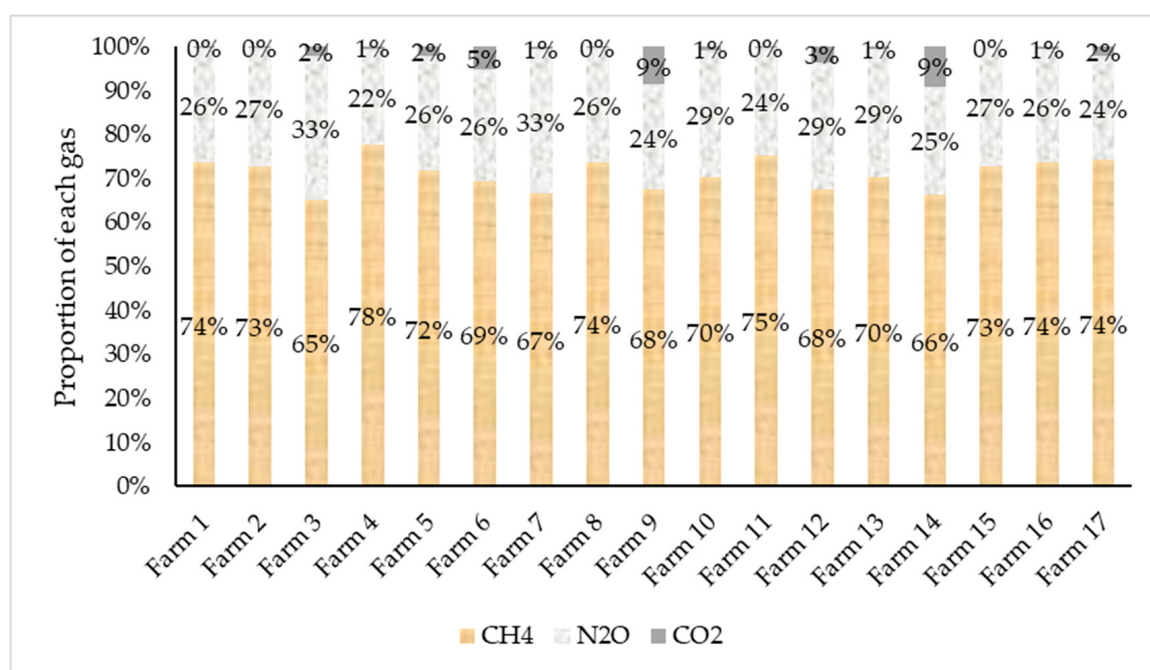


Figure 1. Contribution of each gas to the carbon intensity for the studied farms.

The slaughtering age was strongly correlated with yield-scaled GHG emissions for the studied beef cattle production systems ($p < 0.0001$). In our study, the average age at slaughter was 2 years and 4 months. In 2019, more than 50% of animals were slaughtered at an age of 36 months. In 2003, approximately 50% were slaughtered at an age greater than 48 months [30]. If this annually increasing rate is maintained at less than 10%, the slaughter age can be reduced by more than 36 months. A lower CF was obtained in farms with slaughter ages of 18–24 months. The reported weight at slaughter was 430 kg LW [4,18,32]. However, the potential of slaughtering animals with an LW of 630 kg can be achieved by improving their diet and genetic values [33].

Farm 5 represented a typical Brazilian beef cattle production system. Using a full-cycle production system, an ADG of $\sim 0.3 \text{ kg animal}^{-1} \text{ d}^{-1}$ by the growing animals, stocking rate of 1.09 animal unit (1 AU = 450 kg body weight) and production of 4.26 @ (1@ = 30 kg live body weight) were obtained. In this farm, the CF was 35 kg CO₂eq kg carcass^{−1}, which verified the previous calculations by Cardoso et al. (2016) for a typical farming scenario (39 kg CO₂eq kg carcass^{−1}) [4], even when using updated emission factors and data. These CFs can be used as a reliable measure of sustainability, and farms with values below this are adopting strategies to mitigate GHG impacts.

The lack of site-specific data for calculating soil carbon changes makes it difficult to recommend specific grassland soil management practices to mitigate GHG emissions from animals. An annual change in soil carbon stocks at $\sim 1200 \text{ kg ha}^{-1}$ is required to produce one carcass neutral meat per hectare; de Santos et al. (2019) [34] and de Freitas et al. (2020) [33] demonstrated in their studies that it is possible to achieve this target for more than 20 years.

4. Conclusions

Brazilian beef cattle production is extremely important for the global agro-industrial sector. In this study, the CFs of beef production in 17 representative beef cattle farms in Brazil were calculated using the inventories approach. The impacts of all stages of production from “cradle-to-farm-gate” were analyzed, and possible mitigation strategies in production and animal management operations were identified.

The results showed that the CF of a typical Brazilian beef cattle farm was 35 kg CO₂eq kg^{−1} LW^{−1}. This value verified the previous results reported by Cardoso et al. (2016) when analyzing a prototypical farm [4]. In this study, we used updated emission factors and data, and these values were reliable for developing mitigation strategies to reduce GHG impacts from beef cattle production. A possible limitation of this study is the absence of soil carbon stocks changes that can mitigate GHGs emissions. These average CFs mean that 1222 kg C ha^{−1} is required. Further studies should identify how to increase soil carbon stocks to abate those emissions.

The results indicated that ADG and slaughtering age were the productive variables that had the most influence on the CF. This study presents a significant opportunity to reduce emission intensities associated with beef cattle production. The data obtained herein can be used for several Brazilian beef cattle systems that mostly operate in *Urochloa*, and where feed supplements are primarily composed of corn, soybean meal, and Nellore bread. Future studies should apply the findings of this study by further investigating the specific operations that result in different ADGs and slaughtering ages.

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