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

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 CH$_4$ 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).
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 kg CO$_2$ 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$_2$O) emissions, and N that was lost as ammonia was considered to be volatilized [8]. Direct N$_2$O emissions accounted for 1% of the total nitrogen fertilizer applied to the soil. The volatile fraction of the fertilizer was 15%. Indirect N$_2$O 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$_2$O emission factor was 0.63% of N excreted by the animals. The fraction of volatilized N was 12% [8,24]. Indirect N$_2$O 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 kg CH$_4$ Head$^{-1}$ y$^{-1}$ |
| N$_2$O Direct                   | N$_2$O From Fertilizer = N Applied X EF X 44/28                            | EF = 0.01 kg N$_2$O-N      |
|                                 | N$_2$O From Excreta = N Excreted By The Animals X EF X 44/28               | EF = 0.0063 kg N$_2$O-N    |
|                                 | N$_2$O Indirect Volatization From Fertilizer = N Applied X EF X 44/28       |                           |
| N$_2$O Indirect                 | FRACfert = 15%                                                             | EF = 0.01 kg N Volatilized |
|                                 | N$_2$O Indirect Volatization From Animal Excreta = Nexc X EF X 44/28       |                           |
|                                 | FRACexc = 12%                                                              |                           |

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 kg CH$_4$ 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 ($Y_m$) 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 (CO$_2$eq). The factors used for CO$_2$, fossil CH$_4$, biogenic CH$_4$, and N$_2$O 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 CO$_2(eq$ 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 $^{-1}$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. 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. These productivities were also obtained with strategic animal supplementation. Integrated crop–livestock systems provide higher individual and per area animal production. Legumes such as forage peanut (Arachis pintoi) are promising to obtain high ADG. 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.

### 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    | 0.524                           | 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. A stocking rate potential of 6 AU ha$^{-1}$ in Urochloa grasslands can be achieved using fertilization alone or in combination with animal supplementation. 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 CO\(_2\)eq kg\(^{-1}\) carcass, and varied from 8.6 to 50.9 kg CO\(_2\)eq 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 CH\(_4\), N\(_2\)O, and CO\(_2\), respectively. The contribution of CH\(_4\) varied from 65% to 78%. Nitrous oxide ranged from 22% to 33%, and CO\(_2\) 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 CH\(_4\) production in Brazil [1,6,7,26]. Therefore, to reduce CH\(_4\) emissions, strategies such as increasing the ADG and decreasing the slaughtering age should be prioritized. The highest contribution of N\(_2\)O 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 N\(_2\)O source [28].

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**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 kg animal $^{-1}$ 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 CO$_2$eq kg carcass $^{-1}$, which verified the previous calculations by Cardoso et al. (2016) for a typical farming scenario (39 kg CO$_2$eq 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 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 CO$_2$eq 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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References

1. Ruggieri, A.C.; Cardoso, A.S.; Ongaratto, F.; Casagrande, D.R.; Barbero, R.P.; Brito, L.D.F.; Azenha, M.V.; Oliveira, A.A.; Koscheck, J.F.W.; Reis, R.A. Grazing Intensity Impacts on Herbage Mass, Sward Structure, Greenhouse Gas Emissions, and Animal Performance: Analysis of Brachiaria Pastureland. *Agronomy* 2020, 10, 1750. [CrossRef]

2. Tedeschi, L.O.; Muir, J.P.; Riley, D.G.; Fox, D.G. The role of ruminant animals in sustainable livestock intensification programs. *Int. J. Sustain. Dev. World Ecol.* 2015, 22, 452–465. [CrossRef]

3. McAuliffe, G.A.; Takahashi, T.; Orr, R.J.; Harris, P.; Lee, M.R.F. Distributions of emissions intensity for individual beef cattle reared on pasture-based production systems. *J. Clean. Prod.* 2018, 171, 1672–1680. [CrossRef] [PubMed]

4. Cardoso, A.S.; Berndt, A.; Leytem, A.; Alves, B.J.; de Carvalho, I.D.N.; de Barros Soares, L.H.; Urquiaga, S.; Boddey, R.M. Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use. *Agric. Syst.* 2016, 143, 86–96. [CrossRef]

5. Cardoso, A.S.; Barbero, R.P.; Romanzini, E.P.; Teobaldo, R.W.; Ongaratto, F.; Fernandes, M.H.M.D.R.; Ruggieri, A.C.; Reis, R.A. Intensification: A key strategy to achieve great animal and environmental beef cattle production sustainability in Brachiaria grasslands. *Sustainability* 2020, 12, 6656. [CrossRef]

6. Hoffmann, A.; Cardoso, A.S.; Fonseca, N.V.B.; Romanzini, E.P.; Siniscalchi, D.; Berndt, A.; Ruggieri, A.C.; Reis, R.A. Effects of supplementation with corn distillers’ dried grains on animal performance, nitrogen balance, and enteric CH4 emissions of young Nellore bulls fed a high-tropical forage diet. *Animal* 2021, 15, 100155. [CrossRef] [PubMed]

7. Berça, A.S.; Cardoso, A.S.; Longhini, V.Z.; Tedeschi, L.O.; Boddey, R.M.; Berndt, A.; Reis, R.A.; Ruggieri, A.C. Methane production and nitrogen balance of dairy heifers grazing palisade grass cv. Marandu alone or with forage peanut. *J. Anim. Sci.* 2019, 97, 4625–4634. [CrossRef]

8. Cardoso, A.S.; Oliveira, S.C.; Janusckiewicz, E.R.; Brito, L.F.; Morgado, E.S.; Reis, R.A.; Ruggieri, A.C. Seasonal effects on ammonia, nitrous oxide, and methane emissions for beef cattle excreta and urea fertilizer applied to a tropical pasture. *Soil Tillage Res.* 2019, 194, 104341. [CrossRef]

9. de Klein, C.A.; van der Weerden, T.J.; Luo, J.; Cameron, K.C.; Di, H.J. A review of plant options for mitigating nitrous oxide emissions from pasture-based systems. *N. Z. J. Agri. Res.* 2020, 63, 29–43. [CrossRef]

10. Buratti, C.; Fantozzi, F.; Barbanera, M.; Lascaro, E.; Chiorri, M.; Cecchini, L. Carbon footprint of conventional and organic beef production systems: An Italian case study. *Sci. Total Environ.* 2017, 576, 129–137. [CrossRef]

11. do Nascimento, A.F.; de Oliveira, C.M.; Pedreira, B.C.; Pereira, D.H.; Rodrigues, R.R.D.A. Nitrous oxide emissions and forage accumulation in the Brazilian Amazon forage-livestock systems submitted to N input strategies. *Grassl. Sci.* 2021, 67, 63–72. [CrossRef]

12. BSI. British Standards Institution. PAS 2050:2011. Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services 2011. Available online: https://shop.bsigroup.com/upload/shop/download/pas/pas2050.pdf (accessed on 30 March 2021).

13. MCTI. Fourth National Communication of Brazil to the UNFCCC. 2021. Available online: https://sirene.mctic.gov.br/portal/export/sites/sirene/backend/galeria/arquivos/2020/12/2020_12_22_4CN_v5_Ingles.pdf (accessed on 15 April 2021).

14. Congio, G.F.; Chiavegato, M.B.; Batalha, C.D.; Oliveira, P.P.; Maxwell, T.M.; Gregorini, P.; Da Silva, S.C. Strategic grazing management and nitrous oxide fluxes from pasture soils in tropical dairy systems. *Sci. Total Environ.* 2019, 676, 493–500. [CrossRef]

15. Delevatti, L.M.; Cardoso, A.S.; Barbero, R.P.; Leite, R.G.; Romanzini, E.P.; Ruggieri, A.C.; Reis, R.A. Effect of nitrogen application rate on yield, forage quality, and animal performance in a tropical pasture. *Sci. Rep.* 2019, 9, 7596. [CrossRef]

16. Domiciano, L.F.; Pedreira, B.C.; da Silva, N.M.; Mombach, M.A.; Chizzotti, E.H.; Batista, E.D.; do Nascimento, H.L. Agroforestry systems: An alternative to intensify forage-based livestock in the Brazilian Amazon. *Agrofor. Syst.* 2020, 94, 1839–1849. [CrossRef]

17. Cezimbra, I.M.; de Albuquerque Nunes, P.A.; de Souza Filho, W.; Tischler, M.R.; Genro, T.C.M.; Bayer, C.; de Faccio Carvalho, P.C. Potential of grazing management to improve beef cattle production and mitigate methane emissions in native grasslands of the Pampa biome. *Sci. Total Environ.* 2021, 800, 146882. [CrossRef]

18. Florindo, T.J.; Florindo, G.D.M.; Talamini, E.; da Costa, J.S.; de Leis, C.M.; Tang, W.Z.; Ruviano, C.F. Application of the multiple criteria decision-making (MCDM) approach in the identification of Carbon Footprint reduction actions in the Brazilian beef production chain. *J. Clean. Prod.* 2018, 196, 1379–1389. [CrossRef]

19. Bilotto, F.; Recavarren, P.; Vibart, R.; Machado, C.F. Backgrounding strategy effects on farm productivity, profitability and greenhouse gas emissions of cow-calf systems in the Flooding Pampas of Argentina. *Agri. Syst.* 2019, 176, 102688. [CrossRef]
20. EPE. Balanço Energético Nacional: Relatório Síntese, ano Base 2019. Rio de Janeiro: Ministério de Minas e Energia; 2020. Available online: https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/balanco-energetico-nacional-2019 (accessed on 24 June 2021).

21. IPCC. Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. 2019. Available online: https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/ (accessed on 30 March 2021).

22. Lessa, A.C.R.; Madari, B.E.; Paredes, D.S.; Boddey, R.M.; Urquiaga, S.; Jantalia, C.P.; Alves, B.J. Bovine urine and dung deposited on Brazilian savannah pastures contribute differently to direct and indirect soil nitrous oxide emissions. *Agric. Ecosyst. Environ.* **2014**, *190*, 104–111. [CrossRef]

23. Bretas, I.L.; Paciullo, D.S.; Alves, B.J.; Martins, M.R.; Cardoso, A.S.; Lima, M.A.; Chizzotti, F.H. Nitrous oxide, methane, and ammonia emissions from cattle excreta on *Brachiaria decumbens* growing in monoculture or silvopasture with Acacia mangium and Eucalyptus grandis. *Agric. Ecosyst. Environ.* **2020**, *295*, 106896. [CrossRef]

24. Longhini, V.Z.; Cardoso, A.S.; Berçà, A.S.; Boddey, R.M.; Reis, R.A.; Dubeux Junior, J.C.B.; Ruggieri, A.C. Nitrogen supply and Rainfall affect Ammonia emissions from Dairy Cattle excreta and Urea applied on warm-climate pastures. *J. Environ. Qual.* **2020**, *49*, 1453–1466. [CrossRef]

25. Valadares Filho, S.C.; Costa E Silva, L.F.; Lopes, S.A. BR-CORTE 3.0. Cálculo de Exigências Nutricionais, Formulação de Dietas e Predição de Desempenho de Zebuinos puros e Cruzados. 2016. Available online: https://brcorte.com.br/assets/book2016/br/c0.pdf (accessed on 24 June 2021).

26. Meister, N.C.; Cardoso, A.S.; Alari, F.O.; Lemos, N.L.S.; Frighetto, R.T.S.; Malheiros, E.B.; Reis, R.A.; Ruggieri, A.C. Effect of pasture management on enteric methane emissions from goats. *Trop. Anim. Health Prod.* **2021**, *53*, 1–7. [CrossRef] [PubMed]

27. IPCC. Climate Change 2013: The Physical Science Basis, Contribution of Working Groupe I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 2013. Available online: https://www.ipcc.ch/site/assets/uploads/2018/03/WG1 AR5_SummaryVolume_FINAL.pdf (accessed on 15 April 2021).

28. Boddey, R.M.; Casagrande, D.R.; Homem, B.G.; Alves, B.J. Forage legumes in grass pastures in tropical Brazil and likely impacts on greenhouse gas emissions: A review. *Grass Forage Sci.* **2020**, *75*, 357–371. [CrossRef]

29. ABIEC—Associação Brasileira das Indústrias Exportadoras de Carne. Beef Report: Perfil da Pecuária no Brasil. 2020. Available online: http://abiec.com.br/publicacoes/beef-report-2020/ (accessed on 15 April 2021).

30. Cooke, R.F.; Cardoso, R.C.; Cerri, R.L.; Lamb, G.C.; Pohler, K.G.; Riley, D.G.; Vasconcelos, J.L. Cattle adapted to tropical and subtropical environments: Genetic and reproductive considerations. *J. Anim. Sci.* **2020**, *98*, skaa015. [CrossRef] [PubMed]

31. Vogel, E.; Martinelli, G.; Artuzo, F.D. Environmental and economic performance of paddy field-based crop-livestock systems in Southern Brazil. *Agric. Syst.* **2021**, *190*, 103109. [CrossRef]

32. de Freitas, I.C.; Ribeiro, J.M.; Araújo, N.C.A.; Santos, M.V.; Sampaio, R.A.; Fernandes, L.A.; Frazão, L.A. Agrosilvopastoral systems and well-managed pastures increase soil carbon stocks in the Brazilian Cerrado. *Rangel. Ecol. Manag.* **2020**, *73*, 776–785. [CrossRef]

33. Mota, V.A.; Fernandes, R.M.; Prados, L.F.; Neto, J.A.A.; Berti, G.F.; Resende, F.D.; Siqueira, G.R. Relationship between gain rate during the growing phase and forage allowance in the finishing phase in Nellore cattle. *Trop. Anim. Health Prod.* **2020**, *52*, 1–11. [CrossRef]

34. dos Santos, C.A.; Rezende, C.D.P.; Pinheiro, É.F.M.; Pereira, J.M.; Alves, B.J.; Urquiaga, S.; Boddey, R.M. Changes in soil carbon stocks after land-use change from native vegetation to pastures in the Atlantic forest region of Brazil. *Geoderma* **2019**, *337*, 394–401. [CrossRef]