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# Advanced methodology for the inventory on greenhouse gas emissions in tropical livestock farming

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**Abstract** – The objective of this work was to evaluate the integration of primary regional data into the Tier 2 methodology of Intergovernmental Panel on Climate Change, combined with life cycle assessment, to estimate greenhouse gas (GHG) emissions in beef cattle production. Primary zootechnical and environmental data from 13 modal production systems distributed across 11 microregions of the state of Mato Grosso do Sul, Brazil, were analyzed. Emissions were calculated per unit of area and live weight produced, revealing significant regional variability associated with productive efficiency, pasture management, and overgrazing. The granularity limitations of the fourth national GHG inventory were successfully addressed, resulting in a more accurate, representative, and policy-relevant methodology for estimating emissions from tropical beef cattle systems.

**Index terms**: agricultural sustainability, beef cattle, emission inventory, greenhouse gases, life cycle assessment.

## Metodologia avançada para o inventário de emissões de gases de efeito estufa na pecuária tropical

**Resumo** – O objetivo deste trabalho foi avaliar a integração de dados regionais primários à metodologia Tier 2 do Painel Intergovernamental sobre Mudanças Climáticas, combinada com a avaliação do ciclo de vida, para estimar as emissões de gases de efeito estufa (GEE) na bovinocultura de corte. Foram analisados dados zootécnicos e ambientais primários de 13 sistemas de produção modal, distribuídos em 11 microrregiões do estado de Mato Grosso do Sul, Brasil. As emissões foram calculadas por unidade de área e por peso vivo produzido, revelando variabilidade regional significativa associada à eficiência produtiva, ao manejo de pastagens e à degradação por superpastejo. As limitações de granularidade do quarto inventário nacional de GEE foram superadas com sucesso, tendo resultado em uma metodologia mais precisa, representativa e relevante para políticas públicas, voltada à estimativa de emissões na pecuária de corte em regiões tropicais.

**Termos para indexação**: sustentabilidade agropecuária, pecuária de corte, inventário de emissões, gases de efeito estufa, avaliação do ciclo de vida.

## Introduction

Climate change and global warming remain among the main contemporary challenges, driving the need for a precise measurement of greenhouse gas (GHG) emissions (Hansen et al., 2025). For this, identifying the varying origin and global warming potential of the main GHGs – carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$) – is crucial. While $CO_2$ is primarily related to the burning of fossil fuels, $CH_4$ is mainly emitted by agriculture, especially through enteric fermentation in ruminants (Berndt et al., 2020). In fact, it is estimated that approximately 25% of global GHG emissions are associated with bovine production (Desjardins et al., 2012; D'Aurea et al., 2021; Harfuch & Lemos, 2022).

In this context, it is important to estimate the carbon footprint in livestock farming. However, there is a considerable variability among studies due to methodological differences in data collection and analysis, which should prompt caution when adopting external references outside the intended geographic scope (Ruviaro et al., 2015).

Among the used methods, the tier methodology of Intergovernmental Panel on Climate Change (IPCC) and life cycle assessment (LCA) stand out. The IPCC (2006) methodology organizes emissions by national sectors using standardized emission factors. LCA is a consolidated tool for quantifying the environmental impacts of products or processes throughout their trajectory, from raw material extraction to final disposal, enabling a product-based, bottom-up analysis that accounts for region-specific inputs, management practices, and output levels (Ruviaro et al., 2015). In the present study, LCA complements the IPCC Tier 2 framework by introducing spatial granularity and production system specificity, offering more refined estimates without deviating from international reporting standards. Considered the most robust approach by the European Commission (2010), LCA depends on the quality and suitability of life cycle inventory (LCI) databases. However, many of these databases still use foreign data or are poorly adapted to the reality of beef cattle farming in the main-producing countries, such as Brazil (Ruviaro et al., 2015; Dick et al., 2021; Donnison & Murphy-Bokern, 2024), where more recent national initiatives have been filling this gap (Dias-Filho, 2017, 2023).

The National Emission Registry System (SIRENE) (Brasil, 2023) is the official Brazilian database for anthropogenic emissions and removals of GHGs in the energy, industry, waste, land use, and agriculture sectors. Although it uses consolidated data from sources such as the agricultural census, it still faces limitations related to granularity and regional representativeness (Brazil, 2020). These limitations are especially critical in the livestock sector, where regional factors significantly influence the obtained results.

The present study proposes an advanced and regionalized methodology to estimate GHG emissions in tropical beef cattle farming in Brazil, using primary data and LCA. This regionalized approach is designed to be complementary, replicable, and consistent with the historical series since 1990, as required by the national GHG reporting system (inventory) under the fourth national communication of Brazil to United Nations Framework Convention on Climate Change (Brazil, 2020). Its applications focus on the state of Mato Grosso do Sul, which has a significant role in national beef cattle farming, as it is the second largest beef producer in the country, accounting for 8.83% of national production and for the fifth largest cattle herd (ABIEC, 2024). The state also invests in sustainability through integrated production systems and actions to reduce carbon emissions in livestock farming (Abreu et al., 2025). Although it addresses a specific Brazilian state, the modular structure of LCA allows for replication in other states and biomes of the country by adapting local herd demographics, pasture conditions, and production practices using the same methodological framework.

The objective of this work was to evaluate the integration of primary regional data into the Tier 2 methodology of IPCC, combined with LCA, to estimate GHG emissions in beef cattle production.

## Materials and Methods

In this study, LCA was applied following the ISO 14040/14044 framework of International Organization of Standardization (ISO) (ABNT, 2014, 2025) and adapted to the realities of tropical beef cattle systems. The system boundaries were defined as "cradle-to-farm gate", encompassing all processes from resource extraction to animal-ready-for-slaughter.

The functional unit was 1 kg of live weight (LW) produced. LCI data were regionally collected and included feed composition, animal performance metrics, pasture degradation levels, and use of inputs such as mineral supplements and fossil fuels. Emission factors for methane and nitrous oxide were calculated using the IPCC Tier 2 equations (IPCC, 2006), integrated with LCI parameters to estimate GHG flows. Allocation was avoided by focusing exclusively on the beef output. The integration of LCA with regionalized data allowed for more accurate and spatially sensitive estimates of environmental impacts.

As aforementioned, the adopted methodology integrates the IPCC Tier 2 methodology with LCA to provide regionally adapted GHG estimates. While Tier 2 offers equations and emission factors based on energy intake and manure characteristics, LCA expands the scope by incorporating all upstream and on-farm inputs within a cradle-to-farm gate system boundary. This integration is achieved by using Tier 2 emission calculations (IPCC, 2006) as the core for enteric fermentation and manure management modules, which are embedded within a broader LCA model (ABNT, 2014, 2025) that includes feed production, pasture condition via satellite image using the enhanced vegetation index (EVI), energy use, and mineral supplementation. This hybrid approach ensures consistency with national reporting requirements, while enhancing transparency and spatial resolution. The structure is modular and documented in a replicable framework, adaptable to other regions or production systems.

The methodological stages were three, complementing each other: zootechnical and structural characterization of beef cattle farming in the state of Mato Grosso do Sul by microregion, description of modal production systems, and survey of technical indicators; diagnosis of pasture area conditions in Mato Grosso do Sul; and calculation of GHG emissions based on regional data, integrated with the LCA methodology, with a “cradle-to-farm gate” focus.

In the first stage, data from 2022 available from Agência Estadual de Defesa Sanitária Animal e Vegetal (IAGRO, 2023) were collected, including bovine population, herd structure (sex and age), animal transit guides, slaughters, and geographical coordinates of rural properties. Subsequently, the technical description of the modal production systems was carried out, based on the panel methodology (Platoni et al., 2012; Malafaia et al., 2021), considering the three biomes present in the state, i.e., Cerrado, Pantanal, and Atlantic Forest.

The panels were held between 2014 and 2021, organized by rural unions, with the participation of producers, technicians, and researchers. Thirteen modal systems of beef cattle farming in Mato Grosso do Sul were characterized, covering properties specializing in breeding, rearing, fattening, and the complete cycle. This characterization included management practices, types of feed and forage, use of supplementation, adoption of biotechnologies, stocking rates, and zootechnical indicators. Additional information was obtained from Centro de Estudos Avançados em Economia Aplicada (CEPEA, 2023), which provided parameters such as calving interval, average age of matrices, female and male breeder culling rates, bull/cow ratio, average daily gain, and off-take rate, as well as production costs and economic-financial indicators.

The microregions used as the basis of the analysis were defined according to the territorial division of Instituto Brasileiro de Geografia e Estatística (IBGE, 2025), widely adopted in agricultural statistics. The following 11 microregions were selected for grouping municipalities with similar productive, environmental, and economic characteristics, favoring the representation of the state’s zootechnical diversity: Alto Taquari (18°29'54"S 54°44'49"W), Aquidauana (18°29'54"S 54°44'49"W), Baixo Pantanal (19°01'17"S, 57°38'45"W), Bodoquena (20°32'34"S, 56°40'43"W), Campo Grande (20°27'37"S, 54°37'18"W), Dourados (22°14'01"S 54°47'59"W), Paranaíba (19°40'34"S, 51°11'30"W), Rio Verde de Mato Grosso (18°55'02"S, 54°50'50"W), Ribas do Rio Pardo (20°27'04"S 53°45'32"W), Naviraí (23°03'43"S, 54°12'06"W), and Três Lagoas (20°47'27"S, 51°42'02"W).

In the second stage, the condition of pastures by microregion was evaluated based on satellite images from the MOD13Q1 product of the moderate resolution imaging spectroradiometer (MODIS), using the EVI, according to the methodology of Huete et al. (2002), with normalization and stratification by biome (Lapig, 2022; Mapbiomas, 2022). The areas were classified into three levels of degradation: absent, moderate, and severe (Dias-Filho, 2023), allowing the measurement of carrying capacity and potential impacts on the efficiency of production systems.

In the third stage, the GHG emissions associated with each production system were estimated using the Tier 2 methodology of IPCC (2006) integrated with regional primary data. The main emission sources considered included: enteric fermentation, manure management, fertilizer use, mineral supplementation, fossil fuels, and other agricultural inputs.

The functional unit adopted was the production of 1 kg of final LW at the exit of the production system, on an annual basis. The system boundary comprised all stages from input extraction to animal-ready-for-slaughter, focusing the analysis on emissions directly attributed to the primary phase of livestock production.

The database used for emission modeling included three main categories of information: age and weight, consisting of the classification of the animals into age groups, with respective weight variations throughout the production cycle; diet, characterization of feeding regimes, including pasture types and mineral supplementation; and grazing time, estimation of the average time the animals remained in pasture-based production systems.

Based on this information, GHG emissions were calculated using the following equations for enteric fermentation (EF), manure management (MM), direct and indirect nitrous oxide, and fossil fuels:

EF (kg $CH_4$/kg LW) = (GE × Ym /100)×365 /55.65, where GE is gross energy intake (MJ); Ym is the fraction of gross energy converted into $CH_4$; and 55.65 is the calorific value of $CH_4$ (MJ $kg^{-1}$).

MM (kg $CH_4$/kg DM) = (VS × 365) × [Bo × 0.67 × (MCF / 100)], where VS is volatile solids; Bo is methane generation potential; MCF is the methane conversion factor; and 0.67 is the conversion factor from $m^3$ $CH_4$ to kg $CH_4$.

Direct nitrous oxide (kg $N_2O$/kg N) = EF × N_applied, where EF is the emission factor.

Indirect nitrous oxide (kg $N_2O$/kg N) = EF_leach × N_leach + EF_vol × N_vol, where EF_leach is the emission factor for leaching; N_leach is leached nitrogen; EF_vol is the emission factor for volatilization; and N_vol is volatilized nitrogen.

Fossil fuels (kg $CO_2$/kg fuel) = consumption × EF (Nemecek & Kagi, 2007).

The modeling results were expressed in terms of emissions per hectare (kg $CO_2$eq $ha^{-1}$) and per kilogram of LW produced (kg $CO_2$eq/kg LW), allowing the identification of regional variations and the analysis of the environmental efficiency levels of the systems.

The emission estimates represent a static "snapshot" of the local conditions evaluated, without considering adjustments for productive efficiency or temporal dynamics of management.

The used integrated methodology enables a more precise estimation of regional emissions and offers a robust technical basis for the construction of periodic state-level inventories, compatible with the guidelines of SIRENE (Brasil, 2023).

## Results and Discussion

The characterization of the 11 microregions of the state of Mato Grosso do Sul revealed significant spatial asymmetries, as shown in Table 1. Três Lagoas presented the largest herd in the state (14.89%), followed by Alto Taquari (14.27%) and Baixo Pantanal (13.58%). In contrast, microregions such as Cassilândia (4.21%) and Nova Andradina (5.31%) recorded smaller relative shares. Differences were also observed for mean cattle age and productive aspects. The microregions of Baixo Pantanal and Aquidauana concentrated the largest proportion of adult females (>36 months).

The structural diversity verified across the evaluated microregions is also expressed in public policies to promote meat quality and sustainable production. The Precoce MS program (Mato Grosso do Sul, 2025), for example, aimed at the production of young animals under good agricultural practices, traceability, and low GHG emissions, was concentrated in the microregions of Três Lagoas, Alto Taquari, and Campo Grande, which presented the largest volumes of qualified slaughter. The Carne Sustentável do Pantanal – MS program (Mato Grosso do Sul, 2018) for a sustainable meat production had a greater adherence in the microregions of Baixo Pantanal (52.9%) and Aquidauana (20.86%), which are representative of the Pantanal biome.

The large differences between microregions may due to variations in their territory size, edaphoclimatic conditions, technification degree, and land-use competition with other activities, mainly grain crops and planted forests (Abreu et al., 2025). Such aspects are very likely to affect carbon emission intensity across microregions, mainly because production efficiency is higher and the intensity of GHG emissions is lower in


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intensive rather than extensive systems (McAllister et al., 2020).

Using satellite images from MOD13Q1 of MODIS, combined with the EVI, to evaluate pasture degradation conditions (Huete et al., 2002) allowed discriminating scenarios across the microregions (Figure 1). Only 27.1% of the pasture areas were classified as nondegraded, while 44.7% showed intermediate degradation and 28.2% were in a severe state of degradation. Regions with a high degree of intensification and a large cattle herd presented the worst indicators, which was the case for Três Lagoas, Campo Grande, and Alto Taquari, with only 9.5, 19.3, and 27.2% of nondegraded pastures, respectively. However, regions with extensive management showed better pasture conditions, with Bodoquena leading the ranking (60.5% of nondegraded pastures), followed by Aquidauana (48.4%) and Baixo Pantanal (30.6%), although a high percentage of severe degradation (36.3%) was observed in the former. Pasture degradation has been assumed to be an important factor for GHG emissions in agriculture, since it is related to a higher soil $CO_2$ emission and lower soil carbon stocks (Brito et al., 2015).

The condition of pastures, associated with the zootechnical and economic indicators discussed in the previous sections, reinforces the need for public policies that promote the recovery of degraded areas, especially in regions with overgrazing. Degradation not only compromises the productivity and profitability of farms but also increases the net emission of GHGs per unit of product (Cardoso et al., 2016; Figueiredo et al., 2017). In their study, Oliveira et al. (2020) provided empirical evidence that degraded pastures are associated with a low productivity and significantly higher GHG emissions per unit of product when compared with improved pasture systems such as rainfed medium stocking rate and rainfed high stocking rate. Furthermore, the results obtained by these authors indicate that GHG emission intensity per kilogram of live body weight was the highest in the degraded pasture system, reflecting not only a reduced productivity but also the system's inability to sequester carbon. This leads to greater net GHG emissions per unit of product, reinforcing the importance of pasture restoration and management strategies for a sustainable livestock production.

**Table 1.** Herd characterization by microregion of the state of Mato Grosso do Sul, Brazil, in 2022.

| Microregion | Cattle population (millions) | Slaughter share (%) | Precoce MS program[1] (head) | Carne Sustentável Pantanal – MS program[2] (head) | Females >36 months (%) | Characteristics |
|---|---|---|---|---|---|---|
| Três Lagoas | 2.82 | 15.09 | 184.497 | 0 | 14.2 | Largest herd and technification |
| Alto Taquari | 2.7 | 15.15 | 193.404 | 2.543 | 14.3 | Largest slaughter volume and adherence to Precoce MS |
| Baixo Pantanal | 2.57 | 5.28 | 16.654 | 23.149 | 17.4 | High proportion of matrices and adherence to Carne Sustentável Pantanal – MS |
| Campo Grande | 1.75 | 12.13 | 186.619 | 7.731 | 8.6 | High technification and young animals in Precoce MS |
| Aquidauana | 1.57 | 6.33 | 50.116 | 9.130 | 9.0 | Breeding tradition and Carne Sustentável Pantanal – MS program |
| Bodoquena | 1.81 | 6.97 | 58.342 | 826 | 10.2 | Technical potential and qualified volume |
| Dourados | 1.2 | 7.11 | 46.265 | 262 | 11.5 | Intermediate region with slaughter emphasis |
| Paranaíba | 1.17 | 4.94 | 45.461 | 0 | 13.3 | Moderate breeding and rearing with good technical performance |
| Nova Andradina | 1.01 | 4.98 | 38.837 | 0 | 12.9 | Good adherence to Precoce MS and young productive profile |
| Cassilândia | 0.8 | 3.88 | 21.762 | 0 | 11.8 | Low scale, but good relative performance |
| Iguatemi | 1.53 | 6.14 | 46.630 | 203 | 13.7 | Intermediate, with balance between categories |

[1]Precoce MS is a program for the production of young animals under good agricultural practices, traceability, and low greenhouse gas emissions (Mato Grosso do Sul, 2025). [2]Carne Sustentável Pantanal – MS is a program envisioning a sustainable meat production in the Pantanal (Mato Grosso do Sul, 2018). Source: Agência Estadual de Defesa Sanitária Animal e Vegetal (IAGRO, 2023).

Considering the obtained results, carbon inventories and public policies could eventually benefit from a more precise estimation of pasture degradation in a smaller geographic scope, since large variations were observed across the studied microregions.

Based on the modeling of GHG emissions using regional primary data, it was estimated that beef cattle production in Mato Grosso do Sul totaled 189,954 tonnes of $CO_2$ equivalent. These results correspond to an average of 7.95 kg $CO_2$eq/kg of LW and 4.48 tonnes of $CO_2$eq per hectare.

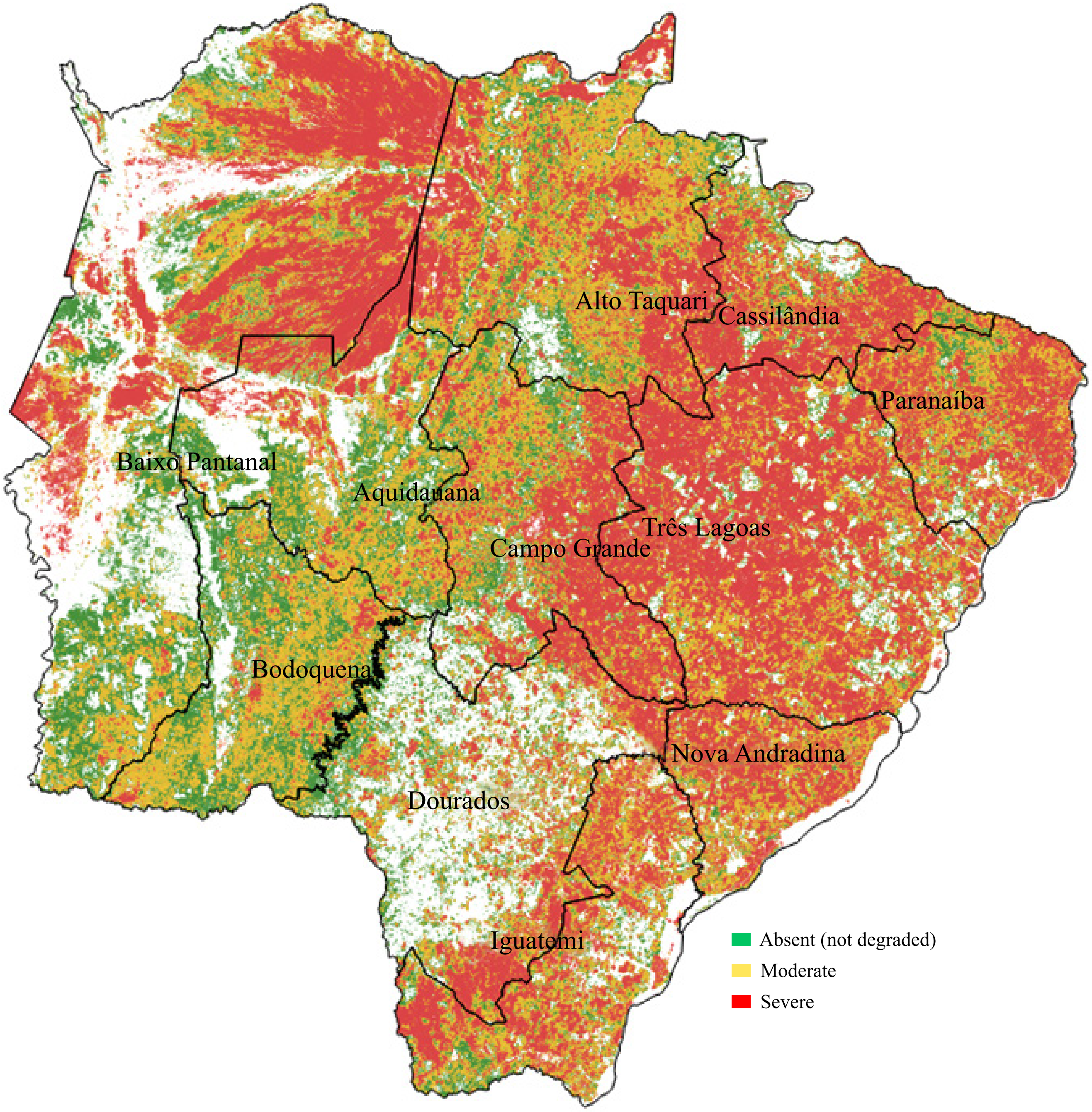


**Figure 1.** Map of pasture conditions by microregion of the state of Mato Grosso do Sul, Brazil, in 2022. Source: data from LAPIG (2022) and Mapbiomas (2022).


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The estimated emissions were associated with the different modal systems distributed across the microregions of Mato Grosso do Sul (Figure 2). The carried-out analysis revealed consistent patterns of environmental performance, strongly influenced by the type of production system, pasture management, and level of technological intensification.

The microregion of Naviraí, located in the Iguatemi region, was represented by modal systems Naviraí 1 and Naviraí 2, which simultaneously stood out among the most productive and, consequently, among the highest emitters per hectare. The Naviraí 2 system, characterized by a high stocking rate, intensive supplementation, and good animal performance, presented the highest emission per hectare of 11,940 kg $CO_2$eq $ha^{-1}$. The Naviraí 1 system recorded high emissions per unit of product of 11.50 kg $CO_2$eq/kg LW. This behavior is consistent with the literature, which indicates that intensification, when not accompanied by mitigation strategies, can result in increased net GHG emissions (Gerber et al., 2013), that is, the stocking rate exerts a strong influence when environmental performance is measured by $CO_2$eq $ha^{-1}$ emissions. While the intensification of pasture-based beef systems may increase GHG emissions per hectare and per animal, mainly due to higher stocking rates and feed intake, it tends to reduce emissions per unit of product, i.e., per kilogram of LW gain or carcass produced (Cardoso et al., 2016; Oliveira et al., 2020).

In the Três Lagoas microregion, two distinct systems were also evaluated. The more intensified Três Lagoas 1 system presented emissions of 5,290 kg $CO_2$eq $ha^{-1}$ and 11.56 kg $CO_2$eq/kg LW, associated with a high pasture degradation (42.8% in severe condition) and an intensive use of inputs. In contrast, the Três Lagoas 2 system, operating with a lower intensity, showed a better environmental performance, with 6.14 kg $CO_2$eq/kg LW, highlighting the role of good management practices in reducing environmental impacts even in contexts of a high livestock density. This finding is supported by investigations that show how good management practices – such as integrated crop-livestock systems, nutritional supplementation, and feedlot finishing – reduce environmental impacts and GHG emissions even under intensified beef

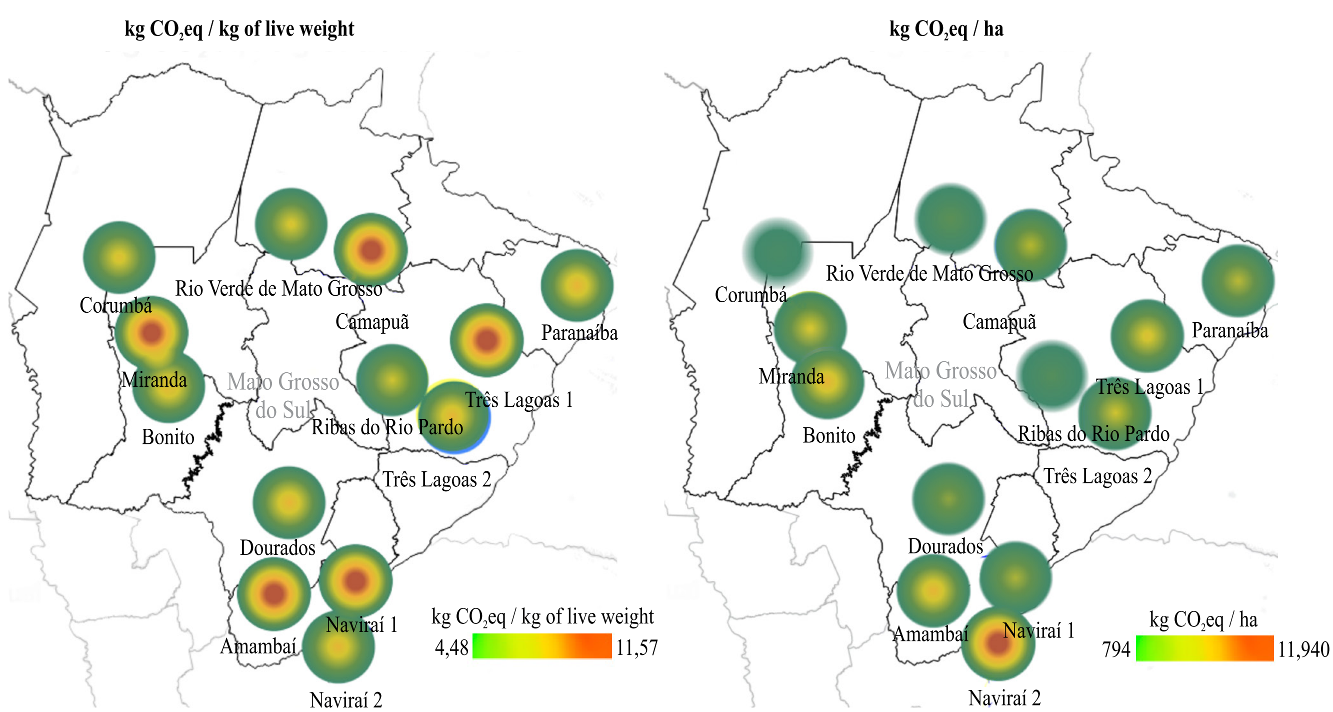


**Figure 2.** Maps of the greenhouse gas emission inventory for beef cattle farming in the state of Mato Grosso do Sul, Brazil, based on emissions per kilogram of live weight produced and per hectare.


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production systems (Kamali et al., 2016; Cardoso et al., 2016)

The microregion of Amambai, also in the Iguatemi region, was represented by a homonymous modal system, which recorded the highest specific emissions of 11.57 kg $CO_2$eq/kg LW. Despite the use of rearing and fattening technologies, the high rate of pasture degradation (56.8% in intermediate or severe condition) compromised environmental performance, confirming that soil degradation increases emissions per unit of product (FAO, 2010). Empirical results presented by Oliveira et al. (2020) indicated that pasture degradation compromises productivity and leads to a considerable increase in GHG emissions per unit of output. In contrast, improved systems, such as rainfed pastures managed under medium and high stocking rates, show a better environmental efficiency.

Regions with smaller-scale production systems and greater ecological balance, such as Rio Verde de Mato Grosso in the Alto Taquari region, presented the best environmental efficiency indices, with only 4.89 kg $CO_2$eq/kg LW and 1,809 kg $CO_2$eq ha$^{-1}$. This microregion illustrates how conservationist practices and good pasture conditions are decisive for emission mitigation. According to Figueiredo et al. (2017), the conversion of a degraded pasture into a well-managed one and the introduction of a crop-livestock-forest integrated system can reduce their associated GHG emissions in terms of kilogram of CO2eq emitted per kilogram of cattle LW produced, increasing the production of meat, grains, and timber. Such reduction is primarily due to pasture improvement and increases in cattle yields, as well as to the provision of technical potential for carbon sinks in soil and biomass to offset cattle-related emissions.

The microregion of Camapuã in Alto Taquari, characterized predominantly by breeding systems, presented emission values of 11.38 kg $CO_2$eq/kg of LW and 4,084 kg $CO_2$eq ha$^{-1}$. These findings are an indicative that, even in extensive systems, inadequate management can result in high specific GHG emissions. In such contexts, pasture degradation – often caused by overgrazing and inadequate practices – compromises productivity and increases emissions per unit of product. Degraded pastures are less efficient in resource use and tend to exhibit a greater emission intensity. In response, the sustainable intensification of beef production, through strategies such as pasture recovery, nutritional supplementation, and crop-livestock integration, emerges as a promising approach to mitigate emissions and improve environmental performance even in traditionally extensive systems (Pereira et al., 2024).

The microregion of Bonito, in the region of Bodoquena, exemplifies a technified rearing and fattening system with a moderate environmental performance of 6.19 kg $CO_2$eq/kg LW and 5,713 kg $CO_2$eq ha$^{-1}$, supported by high rates of pasture conservation, i.e., 60.5% nondegraded.

Other microregions operating under traditional rearing and fattening systems that show a balanced performance include: Paranaíba, with 6.18 kg $CO_2$eq/kg LW and 4,171 kg $CO_2$eq ha$^{-1}$; and Corumbá, in the Baixo Pantanal region, with the lowest absolute emission index of 794 kg $CO_2$eq ha$^{-1}$ despite a moderate individual productivity of 5.22 kg $CO_2$eq/kg LW. The long production cycle and the presence of degraded areas increased the carbon footprint per unit of product, a pattern consistent with the findings of Herrero et al. (2016).

According to Beauchemin et al. (2011), who evaluated different GHG mitigation practices in western Canada, integrated strategies can reduce emissions by up to 20%. In the present study, the variation between microregions in $CO_2$eq ha$^{-1}$ emissions was close to 60%, indicating the potential for significant emission reductions in livestock farming in the state of Mato Grosso do Sul.

Specific emissions (kg $CO_2$eq/kg LW) were, on average, 37% higher in breeding systems compared with rearing and fattening systems, confirming previous findings that the breeding activity is responsible for up to 80% of the carbon footprint of beef (Beauchemin et al., 2011).

The obtained results reinforce that technical efficiency, pasture management, and controlled intensification are key factors for mitigating GHG emissions in tropical livestock farming (Ruviaro et al., 2015).

## Conclusions

1. The proposed methodology estimates regional greenhouse gas emissions with a greater adherence to the productive, ecological, and management characteristics of each microregion of the state of Mato Grosso do Sul, Brazil.

2. The integration of regional primary data with the Tier 2 methodology of Intergovernmental Panel on Climate Change increases estimation accuracy and ensures a greater representativeness of tropical livestock conditions.

3. The generated estimates reflect significant spatial variations driven by management practices, pasture use intensity, and herd zootechnical performance.

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## Data availability statement

The data supporting the findings of this study are available in the article.

## Declaration of use of AI technologies

No generative artificial intelligence (AI) was used in this study.

## Conflict of interest statement

The authors declare no conflicts of interest.

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