Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Enteric methane emissions from male buffaloes in the eastern Amazon: effects of herd age structure using IPCC Tier 1 and Tier 2 approaches

Vinícius Costa Gomes de Castro
Universidade Federal Rural da Amazônia
Lucietta Guerreiro Martorano
Brazilian Agricultural Research Corporation
Jamile Andréa Rodrigues da Silva
Universidade Federal Rural da Amazônia
Natália Guarino Sousa Barbosa
Universidade Federal Rural da Amazônia
José Reinaldo da Silva Cabral de Moraes
Brazilian Agricultural Research Corporation
João Maria do Amaral Júnior
Instituto Federal do Amapá
Paulo Campos Christo Fernandes
Brazilian Agricultural Research Corporation
Welligton Conceição da Silva
Universidade Federal do Pará
Thomaz Cyro Guimarães de Carvalho Rodrigues
Universidade Federal de Roraima
Éder Bruno Rebelo da Silva
Universidade Federal do Pará
Leonel António Joaquim
jleokim.a@hotmail.com
Instituto de Investigação Agrária de Moçambique
Laíza de Kássia Mendes da Conceição
Universidade Federal do Pará
Mariana Jucá Moraes
Universidade Federal do Pará
Patricia Perondi Anchão Oliveira
Brazilian Agricultural Research Corporation
Anna Patrycia Martins de Oliveira
Universidade Federal do Pará
João Vitor da Silva Oliveira
Universidade Federal do Pará
José de Brito Lourenço Júnior
Universidade Federal do Pará

Article

Keywords: herd structure, age class, emission inventory, pasture management, animal retention, multivariate analysis

Posted Date: October 5th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10932131/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: No competing interests reported.

Abstract

Buffalo production in Pará State, eastern Amazon, Brazil, is largely based on extensive pasture systems, in which herd age structure, animal performance, and retention time can influence accumulated enteric methane emissions. In this study, we estimated enteric CH_4 emissions from male buffaloes from 2006 to 2025 using the Intergovernmental Panel on Climate Change Tier 1 and Tier 2 approaches. Herd data stratified by age class were obtained from the Agriculture and Livestock Defense Agency of Pará State. Tier 1 estimates used a fixed emission factor of 68 kg CH_4 animal^{-1} year^{-1}, whereas Tier 2 estimates used age-specific emission factors derived from animal weight, weight gain, feed intake, digestibility, and energy requirements. Statistical analyses included age-class contribution, Pearson correlation, principal component analysis, hierarchical clustering, and cluster projection. Tier 2 emission factors increased with age, from 15.65 kg CH_4 animal^{-1} year^{-1} in animals aged 4–12 months to 58.11 kg CH_4 animal^{-1} year^{-1} in animals older than 36 months. Animals older than 36 months accounted for the highest mean contribution to total Tier 2 emissions, reaching 38.0%. The years 2010, 2011, and 2021 showed the strongest influence of adult animal retention on total emissions. The first two principal components explained 91.3% of the total variance and separated 2010 and 2011 as years with atypical adult retention. These results demonstrate that emissions were driven by herd size and age-class composition. Improving pasture quality, nutritional management, zootechnical control, and slaughter planning may lower accumulated CH_4 emissions in Amazonian buffalo systems under regional production conditions.

1. Introduction

Climate change has intensified the demand for accurate greenhouse gas (GHG) inventories and mitigation strategies capable of supporting national commitments under international agreements. In livestock systems, methane (CH_4) deserves special attention because it is directly associated with enteric fermentation in ruminants and represents an important component of agricultural emissions reported in national inventories (Gavrilova et al., 2019). Brazil has committed to reducing net GHG emissions by 59 to 67% by 2035, relative to 2005 levels, which reinforces the need to improve the precision of emission estimates in all productive sectors, including agriculture and livestock (MCT, 2024).

Food production must respond simultaneously to climate commitments and to the growing demand for safe, high-quality food. Brazil occupies a strategic position in this context because its agricultural and livestock sectors combine territorial scale, productive diversity, pasture-based animal production, and strong participation in international markets (Adedeji et al., 2014). Therefore, improving GHG accounting in Brazilian livestock systems is not only an environmental requirement, but also a scientific and economic priority for maintaining competitiveness, transparency, and credibility in global food chains (Gavrilova et al., 2019).

Animal protein consumption remains an important component of food systems, and international markets increasingly require products linked to traceability, environmental responsibility, and robust emission accounting. In 2022, Brazilian beef exports represented 27.96% of national beef production, confirming the relevance of the country as a global supplier of animal protein (Adedeji; Reuben and Olatoye, 2014). In this context, cattle and buffalo production systems raised predominantly on pasture must be evaluated with methods capable of distinguishing between poorly managed systems and systems that improve pasture quality, animal performance, and the age at which animals leave the farm (Gavrilova et al., 2019; Malla et al., 2022).

In ruminant production, enteric CH_4 emissions depend on feed intake, diet composition, digestibility, animal category, body weight, weight gain, and time spent in the production system (Ahmed et al., 2023; Malla et al., 2022). For this reason, emission estimates based only on herd size may mask important differences among production systems, especially in tropical regions where pasture quality, supplementation, management, and animal performance vary widely (Ahmed et al., 2023). The use of regional data and more detailed calculation approaches is therefore essential to reduce uncertainty and to generate estimates that are compatible with the real conditions of livestock production (Martorano et al., 2021).

The Brazilian pasture-based system has an important advantage when animals are efficiently managed and reach slaughter weight earlier. In these systems, the length of the production cycle becomes a key variable, because animals retained for longer periods continue emitting CH_4 throughout their residence time on farms (Malla et al., 2022; Martorano et al., 2021). Thus, better pasture management, improved nutrition, higher daily weight gain, and animal removal before or around 36 months of age may reduce cumulative enteric CH_4 emissions compared with systems that retain adult males for longer periods (Martorano et al., 2021; Xue; Wang and Yan, 2014).

This discussion is particularly relevant for the state of Pará, in the eastern Amazon, where cattle and buffalo production occur under heterogeneous pasture conditions and strong territorial contrasts (Lanzoni et al., 2022). Buffalo production deserves specific attention because buffaloes remain less represented than cattle in GHG assessments, despite their relevance in tropical livestock systems and their capacity to occupy environments where other ruminants may be less adapted (Xue et al., 2014). Studies on buffalo and cattle methane inventories show that species, animal category, production system, and methodological tier influence CH_4 estimates, reinforcing the need for regional and species-specific approaches (Xue; Wang and Yan, 2014).

The Intergovernmental Panel on Climate Change (IPCC) recommends different methodological levels for livestock emission inventories. Tier 1 uses default emission factors and requires only animal population data, whereas Tier 2 incorporates animal category, body weight, weight gain, feed digestibility, energy requirements, and methane conversion factors (Gavrilova et al., 2019). Therefore, Tier 2 is more appropriate for evaluating production systems in which herd structure and productive conditions vary over time, as occurs in pasture-based buffalo systems in the Amazon (Gavrilova et al., 2019; Xue; Wang and Yan, 2014).

To calculate enteric CH_4 emissions from male buffaloes in Pará, eastern Amazon, from 2006 to 2025 using IPCC Tier 1 and age-structured Tier 2 approaches, and to evaluate whether annual emissions were driven only by herd size or also by age-class composition. We hypothesized that the retention of animals older than 36 months increases cumulative CH_4 emissions and that the use of regionalized age-structured calculations improves the interpretation of buffalo emissions within GHG inventory frameworks.

2. Materials and Methods

2.1. Study area, herd data, and feeding information

This study used secondary official data and did not involve animal handling, experimental procedures, or biological sample collection. Therefore, approval by an ethics committee on animal use was not required. It was conducted for the state of Pará, located in the eastern Brazilian Amazon. Pará comprises territories with marked differences in climate, land use, pasture conditions, and livestock production systems. For regional characterization, the state was considered according to its six mesoregions: Lower Amazon, Marajó, Belém Metropolitan Area, Northeast Pará, Southeast Pará, and Southwest Pará.

The historical series of the male buffalo herd in Pará from 2006 to 2025 was obtained from the Agriculture and Livestock Defense Agency of the State of Pará (ADEPARA). The database came from annual livestock inspections and included the number of male buffaloes stratified into four age classes: 4 to 12 months, 12 to 24 months, 24 to 36 months, and older than 36 months (Table 1). These age classes were used as the demographic basis for estimating enteric CH_4 emissions under the IPCC Tier 1 and age-structured Tier 2 approaches.

Table 1 shows that the male buffalo herd varied not only in total size, but also in age-class composition over time. The total number of male buffaloes ranged from 107,738 animals in 2009 to 291,361 animals in 2025. Years such as 2010 and 2011 showed an atypical concentration of animals older than 36 months, which represented 44.3% and 46.4% of the total male herd, respectively. In contrast, 2025 showed the highest total herd size, with 101,499 animals in the youngest age class and 66,608 animals older than 36 months. Therefore, Table 1 provides the demographic basis for comparing Tier 1 estimates, which depend only on total herd size, with age-structured Tier 2 estimates, which respond to the distribution of animals among age classes.

Information on forage resources, supplementation, animal nutrient requirements, body weight, and daily weight gain was obtained from the literature and used to support the Tier 2 calculations. These parameters allowed the estimation of energy requirements and age-specific emission factors according to the methodological assumptions adopted for ruminant methane inventories.

Table 1
Number of male buffaloes by age category in the state of Pará, eastern Amazon, Brazil, from 2006 to 2025.

Year	4–12 months	12–24 months	24–36 months	> 36 months	Total
2006	46,274	35,670	33,722	31,163	146,829
2007	37,510	38,032	32,716	16,470	124,728
2008	40,026	40,168	31,533	15,266	126,993
2009	30,863	34,907	28,131	13,837	107,738
2010	33,313	40,992	35,086	86,928	196,319
2011	34,078	42,065	32,680	94,387	203,210
2012	47,175	40,919	34,585	34,623	157,302
2013	42,948	42,750	36,368	34,040	156,106
2014	45,721	43,187	35,856	40,949	165,713
2015	46,322	44,823	37,473	35,504	164,122
2016	47,186	43,348	37,373	45,549	173,456
2017	58,207	47,873	34,949	48,918	189,947
2018	52,547	50,638	38,370	54,800	196,355
2019	61,921	47,362	49,208	35,735	194,226
2020	59,232	50,084	41,008	32,271	182,595
2021	68,940	56,529	60,740	82,680	268,889
2022	74,113	59,340	43,908	64,667	242,028
2023	72,831	63,749	46,964	70,015	253,559
2024	67,136	60,638	42,660	56,435	226,869
2025	101,499	71,473	51,781	66,608	291,361

2.2. IPCC methodology

Enteric methane emissions were estimated according to the methodological framework proposed by the IPCC for livestock inventories, using Tier 1 and Tier 2 approaches (Gavrilova et al., 2019; Jiao et al., 2014). These approaches allowed CH_4 emissions to be interpreted both as a function of total herd size and as a response to age-class composition and productive characteristics of the male buffalo herd.

Under the Tier 1 approach, emissions are estimated using a single default emission factor applied to the total animal population. This method requires only animal population data and provides a broad estimate of enteric CH_4 emissions. Under the Tier 2 approach, emissions are estimated by animal subcategory, incorporating specific emission factors associated with age, body weight, weight gain, feed intake, digestibility, and energy requirements (Gavrilova et al., 2019; Jiao et al., 2014). Therefore, total enteric CH_4 emissions from male buffaloes were obtained by summing the emissions estimated for each age class according to the corresponding emission factor and methodological approach.

2.2.1. Tier 1

The Tier 1 approach was applied to the male buffalo herd from 2006 to 2025 using a fixed emission factor. The enteric methane emission factor adopted for buffaloes was 68 kg CH_4 animal^{-1} year^{-1}. Total emissions were estimated by multiplying this emission factor by the number of animals and converting the result to gigagrams of CH_4 per year, according to Eq. 1:

$$\text{Emissions} = 68 \times (\text{N}/10^6) \quad (1)$$

in which: Emissions = methane emissions from enteric fermentation, Gg CH_4 yr^{-1}; N = number of male buffaloes.

2.2.2 TIER 2

The Tier 2 approach was applied by estimating enteric CH_4 emissions separately for each age class of male buffaloes and then summing the emissions across all classes. This procedure allowed the calculations to incorporate differences in age structure, body weight, average daily weight gain, feeding intake, diet digestibility, and energy requirements, rather than assuming a single fixed emission factor for the entire herd (Gavrilova et al., 2019).

Body weight and average daily weight gain for each age class were used to estimate dry matter intake and energy demand. The calculations considered feeding condition, pasture condition, animal category, feed digestibility, herd size, and time spent on pasture, following the assumptions recommended for Tier 2 livestock methane inventories (Gavrilova et al., 2019). Total enteric CH_4 emissions were obtained by multiplying the number of animals in each age class by its corresponding Tier 2 emission factor and then summing the estimated emissions across age classes.

Net energy requirements were calculated for maintenance, activity, growth, and work. The net energy for maintenance was estimated according to Eq. 2:

$$\mathrm{NEm} = (\mathrm{Cfi} \times \mathrm{LW})^{0.75}$$

2

in which: E_{CH_4} NEm: net energy for maintenance in MJ day^{-1}; Cfi: coefficient varying for each category, (0.37 for male buffaloes); LW: animal live weight in kg.

The requirement of net energy for daily activities is measured by Eq. (3):

$$\mathrm{NEa} = \mathrm{Ca} \times \mathrm{NEm}$$

3

in which: NEa: net energy for animal activity in MJ.day^{-1}; Ca: coefficient of the animal's dietary situation (0.17 for buffaloes on delimited pasture and 0.36 for buffaloes on open pasture); and NEm: net energy for maintenance in MJ day^{-1}.

Equation (4) estimated net energy for growth:

$$\mathrm{NEg} = 22.2 \times \left(\frac{\mathrm{LW}}{\mathrm{C}} \times \mathrm{MW}\right)^{0.75} \times \mathrm{WG1.097}$$

4

in which: NEg: net energy for growth in MJ day^{-1}; LW: mean live weight of the animals in the population in kg; C: coefficient with values of 0.8 for females, 1 for castrated males, and 1.2 for whole males; MW: body maturity weight of the animals in kg; WG: mean daily weight gain of the animals in kg day^{-1}.

Equation (5) estimated the ratio between net energy available in the diet for maintenance and digestible energy consumed was:

$$\mathrm{REM} = [1.123 - (4.092 \times 10 - 3 \times \mathrm{DE}\backslash\%) + [1.126 \times 10 - 5 \times (\mathrm{DE}\backslash\%)^2]$$

5

in which: REM: ratio between net energy available in the diet for maintenance and digestible energy consumed; DE%: digestible energy as a percentage of raw energy.

Equation (6) was used to estimate the ratio between net energy available in the diet for maintenance and digestible energy consumed:

$$\mathrm{REG} = [1.164 - (5.160 \times 10 - 3 \times \mathrm{DE}\backslash\%) + [1.308 \times 10 - 5 \times (\mathrm{DE}\backslash\%)^2]$$

6

in which: REG: ratio between net energy available in the diet for growth and digestible energy consumed; DE%: digestible energy as a percentage of raw energy.

The equations REM and REG relate the net energy available in the feed to the requirements for growth and maintenance and are used to calculate the raw energy requirement for each animal in its category.

The raw energy requirement was estimated by Eq. (7):

$$\mathrm{RE} \; = \; \{ [\, (\mathrm{NEm} + \mathrm{NEa}) / \mathrm{REM}] + \mathrm{NEg} / \mathrm{REG} \} / \mathrm{DE} / 100$$

7

in which: RE: raw energy in MJ day^{-1}; NEm: net energy required by the animal for maintenance in MJ day-1; NEa: net energy for animal activity in MJ day-1; REM: ratio between net energy available in the diet for maintenance and digestible energy consumed; NEg: net energy required for growth in MJ day^{-1}; REG: ratio between net energy available for growth in the diet and digestible energy consumed and DE in %: digestible energy expressed as percentage of raw energy.

The emission factor in kg of CH_4 head^{-1} day^{-1} (EF) is described by Eq. (8). The emission factors selected were multiplied by the animal population, associated to age categories, and summed and converted into gigagrams (Gg).

$$\mathrm{EF} \; = \; \{ \left[\mathrm{RE} \times \; \left(\frac{\mathrm{Ym}}{100} \right) \right] \times \; 365 \} / 55.65$$

8

in which: RE: raw energy intake in MJ head^{-1} day^{-1}; Ym: methane conversion factor contained in the feed at 6.5% ± 1% for buffaloes reared on pasture.

2.3. Statistical and multivariate analysis

Statistical and multivariate analyses were performed to evaluate temporal variation in enteric CH_4 emissions and to identify the influence of herd age structure on emission patterns. This analytical step was central to the study because it allowed the temporal behavior of emissions to be interpreted not only from total herd size, but also from changes in the proportional distribution of animals among age classes.

Six variables were selected for the multivariate analysis: total CH_4 emissions estimated using the Tier 1 approach, total CH_4 emissions estimated using the Tier 2 approach, and the percentage contribution of each age class to the total male buffalo herd: 4–12 months, 12–24 months, 24–36 months, and older than 36 months. These variables were selected because they represent the two main dimensions of the study: emission magnitude and herd age-class composition.

Before multivariate analysis, all variables were standardized using z-scores to remove scale effects and allow direct comparison among variables expressed in different units. Principal component analysis was used as an integrative approach to reduce dataset dimensionality and identify the main gradients associated with temporal variation in CH_4 emissions and herd structure. In this analysis, years were considered as observations, whereas emission estimates and age-class percentages were considered as explanatory variables.

Hierarchical cluster analysis was applied to the standardized dataset to group years with similar multivariate profiles. Clustering was performed using Euclidean distance and Ward's linkage method. This procedure allowed the identification of years with similar combinations of herd age structure and emission patterns, highlighting periods in which the retention of older animals could influence total CH_4 emissions.

Pearson correlation analysis was also performed to evaluate the association between age-class composition and total CH_4 emissions estimated using the Tier 1 and Tier 2 approaches. Together, principal component analysis, hierarchical clustering, and correlation analysis provided a complementary statistical framework to assess whether emission dynamics were driven only by herd size or also by changes in the age structure of the male buffalo herd.

3. Results

The relationship between herd age classes and enteric CH_4 emissions differed between the Tier 1 and Tier 2 approaches. Total CH_4 emissions estimated by Tier 1 and Tier 2 showed a similar overall temporal pattern, but the interpretation of emission drivers changed when age-class composition was considered. Under Tier 1, total CH_4 emissions were most strongly correlated with the 12–24-month age class, reflecting the use of a single fixed emission factor applied uniformly to all animals. In contrast, under Tier 2, total CH_4 emissions were most

strongly correlated with animals older than 36 months, indicating that this approach was more sensitive to adult animal retention and age-specific emission potential.

The mean contribution of each age class to total CH_4 emissions also differed between approaches. Under Tier 1, the contribution of age classes was more evenly distributed, ranging from 21.3% to 28.4%. Under Tier 2, the relative contribution shifted toward older animals, with the > 36-month category accounting for 38.0% of total CH_4 emissions. These results show that Tier 2 better captured the effect of animal age, body development, and longer retention time in the herd, whereas Tier 1 mainly reflected total herd size. This combined pattern of correlation and contribution is presented in Table 2.

Table 2
Relationship between herd age classes and enteric CH_4 emissions estimated using Tier 1 and Tier 2 approaches from 2006 to 2025.

Age class	Correlation with total Tier 1 CH_4	Correlation with total Tier 2 CH_4	Mean contribution to Tier 1 total CH_4 (%)	Mean contribution to Tier 2 total CH_4 (%)
4–12 months	0.841	0.677	28.4	12.3
12–24 months	0.912	0.796	25.8	22.9
24–36 months	0.841	0.758	21.3	26.9
> 36 months	0.787	0.916	24.4	38.0
Note: Age classes were standardized as 4–12, 12–24, 24–36, and > 36 months to match the herd database used in the study.				

Table 3 presents the enteric methane emission factors used to estimate CH_4 emissions under the Tier 1 and Tier 2 approaches. In the Tier 1 approach, a single fixed emission factor of 68 kg CH_4 animal^{-1} year^{-1} was applied to all age classes, regardless of animal age, body weight, feed intake, digestibility, or energy requirements. In contrast, Tier 2 emission factors varied according to age class, increasing from 15.65 kg CH_4 animal^{-1} year^{-1} in animals aged 4–12 months to 58.11 kg CH_4 animal^{-1} year^{-1} in animals older than 36 months. This gradient shows that Tier 2 incorporated biological and nutritional differences among age classes, allowing emissions to be interpreted according to animal development and retention time in the herd.

Table 3
Enteric methane emission factors used to estimate CH_4 emissions from male buffaloes under Tier 1 and age-structured Tier 2 approaches.

Age class	Tier 1 CH_4 emission factor	Tier 2 CH_4 emission factor
4–12 months	68.00	15.65
12–24 months	68.00	32.17
24–36 months	68.00	45.76
> 36 months	68.00	58.11
Note: Emission factors are expressed in kg CH_4 animal^{-1} year^{-1}.		

Principal component analysis was used to jointly evaluate the relationship between herd age-class composition and enteric CH_4 emissions estimated using Tier 1 and Tier 2 approaches. This analysis represented the main integrative step of the results because it allowed emission patterns to be interpreted simultaneously with changes in herd structure. The first two principal components explained 91.3% of the total variance, with PC1 accounting for 70.0% and PC2 accounting for 21.3%. This high cumulative explanation indicates that the selected variables effectively summarized the temporal variability in herd composition and CH_4 emissions.

The PCA biplot showed a clear separation among years according to emission magnitude and age-class composition. Years positioned on the positive side of PC1 were associated with higher total CH_4 emissions estimated by both Tier 1 and Tier 2. The vectors representing total emissions under Tier 1 and Tier 2 pointed in the same general direction, confirming that both approaches followed a similar broad temporal pattern. However, the Tier 2 emission vector was more closely aligned with the vector representing animals older than 36 months, indicating that Tier 2 was more sensitive to adult animal retention and age-specific emission potential.

The use of different colors for the vectors strengthened the interpretation of the biplot by clearly separating herd age classes from total emission estimates. This visual structure made it easier to identify the contrast between years associated with younger animals and years

associated with greater participation of adult animals, as well as the different relationships of Tier 1 and Tier 2 with herd composition. In this sense, the PCA was particularly important because it provided not only statistical synthesis, but also an integrated visual representation of the biological and demographic processes underlying enteric CH_4 emissions.

The years 2010 and 2011 were clearly separated from most of the time series and were strongly associated with the proportion of animals older than 36 months. This pattern confirms that these years were characterized by an atypical accumulation of adult males in the herd. The year 2021 also showed a high-emission profile and was positioned near the Tier 2 emission vector, indicating that its emission increase was associated with both herd expansion and a greater contribution of adult animals. In contrast, years such as 2007, 2008, and 2009 were positioned on the negative side of PC1, reflecting lower total emissions and lower participation of animals older than 36 months.

The opposite direction of the vectors representing younger age classes and animals older than 36 months indicates a structural contrast in the herd over time. Years with a greater proportion of young animals were separated from years marked by adult animal retention. This result demonstrates that age-class composition substantially influenced CH_4 emission estimates, especially under the Tier 2 approach. Therefore, the multivariate analysis supports the central interpretation of this study: Tier 2 provides a more detailed and biologically meaningful representation of enteric methane emissions from male buffaloes, particularly when animal retention time in the production system varies among years (Fig. 1).

Hierarchical clustering confirmed the multivariate structure observed in the PCA and grouped the years according to similarities in herd age-class composition and enteric CH_4 emission patterns. The dendrogram separated the time series into three main profiles: years with lower emission magnitude and lower participation of adult animals; years with atypical retention of animals older than 36 months; and more recent years associated with higher emission levels and herd expansion (Fig. 2).

The first cluster grouped years such as 2007, 2008, and 2009, which were characterized by lower total herd size and lower participation of animals older than 36 months. This group also included years such as 2006, 2012, 2013, 2014, 2015, 2016, 2019, and 2020, indicating a broader multivariate profile with moderate emissions and greater similarity in herd age-class distribution. Within this cluster, the proximity between 2007 and 2008, as well as between 2014 and 2016 and between 2006 and 2012, suggests years with similar demographic and emission patterns.

The years 2010 and 2011 formed a distinct and very close subgroup, confirming their atypical behavior in the historical series. This separation reflects the high proportion of animals older than 36 months in those years and reinforces the interpretation that adult male retention strongly influenced the emission pattern. The short linkage distance between 2010 and 2011 indicates that these two years shared a highly similar herd structure, marked by adult animal accumulation.

A third cluster grouped years with higher emission profiles, including 2021, 2025, 2017, 2018, 2024, 2022, and 2023. Within this group, 2022 and 2023 were the closest years, followed by their association with 2024, indicating a recent pattern of similarity in herd composition and CH_4 emissions. The years 2017 and 2018 also formed a close subgroup, while 2021 and 2025 were associated with this high-emission cluster but showed greater separation, reflecting their distinct contribution to the temporal dynamics of the herd.

Overall, the hierarchical clustering supports the central result of this study: annual enteric CH_4 emissions from male buffaloes were not determined only by total herd size, but also by the distribution of animals among age classes. The proximity among years within each cluster shows that similar demographic structures generated similar emission profiles. Therefore, the clustering analysis complements the PCA by confirming that Tier 2 provides a more informative interpretation of years marked by adult animal retention and age-structured emission dynamics.

The cluster projection onto the PCA space provided a clearer visualization of the three multivariate profiles identified in the time series (Fig. 3). The green cluster represented years with lower emission profiles, including 2006, 2007, 2008, 2009, 2012, 2013, 2014, 2015, 2016, 2019, and 2020. These years were positioned mostly on the negative side of PC1 and were associated with lower total CH_4 emissions or more balanced age-class composition.

The red cluster represented the adult-retention profile and included only 2010 and 2011. These two years were clearly separated from the remaining time series and were positioned in the lower-right portion of the PCA space, indicating a distinct demographic structure marked by the accumulation of animals older than 36 months. This pattern reinforces that the retention of adult males created a specific emission profile that was not explained only by total herd size.

The orange cluster represented years with higher emission profiles and included 2017, 2018, 2021, 2022, 2023, 2024, and 2025. These years were positioned mainly on the positive side of PC1 and reflected greater total CH_4 emissions associated with herd expansion and, in some

years, a greater contribution of older animals. The position of 2021 within this cluster confirms its high-emission profile, although it remained distinct from the atypical adult-retention pattern observed in 2010 and 2011.

4. Discussion

The results of this study show that enteric CH_4 emissions from male buffaloes in Pará were not determined only by total herd size, but also by changes in herd age-class composition, especially the retention of animals older than 36 months. This interpretation is consistent with the methodological distinction between Tier 1 and Tier 2 approaches. Tier 1 applies a single fixed emission factor to all animals and mainly reflects population size, whereas Tier 2 incorporates age-specific emission factors and provides a more sensitive estimate of biological and productive differences among animal categories (Gavrilova et al., 2019; Jiao et al., 2014).

The methodological comparison with Brazilian references reinforces the contribution of the present study to livestock GHG accounting (Estevão; Pavão and Assad, 2023; Genro; Lara and Lamperti, 2023). These references show that national emission estimates depend on inventory structure, emission factors, metrics, assumptions, and the degree of regionalization adopted in the calculation. In this context, the present study follows the IPCC inventory logic but advances the interpretation of enteric CH_4 emissions by incorporating species, age class, regional herd structure, and animal retention time in male buffaloes from Pará.

.

Table 4
Methodological comparison between the present study and Brazilian references on livestock GHG accounting.(*CH_4 = methane; IPCC = Intergovernmental Panel on Climate Change; GHG = greenhouse gas)*

Reference	Species and region	Method	Emission factor / basis
WRI Brasil, (2015)	Cattle and livestock systems, Brazil / Pará	IPCC Tier 1 and Tier 2	For Pará cattle: 53, 41, 60, and 63 kg CH_4 $head^{-1}$ $year^{-1}$
Estevão; Pavão and Assad, (2023)	Livestock systems, Brazil	Review of factors, metrics, and methods	Emissions depend on factors, metrics, systems, and assumptions
(Genro; Lara and Lamperti, (2023)	Beef cattle, Rio Grande do Sul	IPCC Tier 1 and Tier 3	Tier 1: 56 kg CH_4 $head^{-1}$ $year^{-1}$; Tier 3: 48 to 51 kg CH_4 $head^{-1}$ $year^{-1}$
Present study	Male buffaloes, Pará, eastern Amazon	IPCC Tier 1 and age-structured Tier 2	Tier 1: 68 kg CH_4 $animal^{-1}$ $year^{-1}$; Tier 2: 15.65 to 58.11 kg CH_4 $animal^{-1}$ $year^{-1}$ according to age class

The comparison presented in Table 4 reinforces that the present study is aligned with inventory-based GHG accounting but also shows that regional interpretation is essential when herd structure varies over time. In this sense, the choice of metric, emission factor, and methodological tier affects the way livestock emissions are interpreted, particularly when methane is evaluated in relation to national commitments and agricultural production systems (Plattner et al., 2009). Climate projections and long-term climate datasets have already shown that global warming changes the environmental conditions under which agriculture and livestock operate, reinforcing the need for emission estimates that are consistent across time and regions (Meehl et al., 2007).

In Brazil, this discussion is directly connected to climate policy, national reporting, and land-use governance. Commitments under international agreements require that agricultural emissions be estimated with transparency and methodological consistency (Bolson and Araújo, 2022). National communications and emission inventories provide the institutional basis for reporting anthropogenic emissions and removals, including those associated with agriculture, livestock, and land-use change (MCT, 2016). In regions where deforestation, pasture expansion, and livestock production interact, the valuation and accounting of GHG emissions become particularly relevant for interpreting the environmental performance of production systems (Lima; Macedo and Vignandi, 2023).

The relationship between land use, climate change, food security, and livestock production is also central to the interpretation of the present results. Climate change affects forage availability, soil conditions, animal thermal comfort, and productive efficiency, while agricultural and livestock systems also contribute to GHG emissions (Aryal et al., 2019; Mbow et al., 2022; Praveen and Sharma, 2019). Adaptation and mitigation strategies in agriculture increasingly emphasize the need to combine productivity gains, climate-smart practices, better land management, and more efficient use of already anthropized areas (Abegunde; Sibanda and Obi, 2019; Azadi et al., 2022). Therefore, the present findings should be interpreted not only as an emission inventory exercise, but also as evidence that herd management can influence the climate performance of buffalo production systems.

The social and economic perception of climate risk also affects how livestock systems respond to mitigation demands. Studies on farmers and agricultural advisors have shown that climate risk is not interpreted only as a biophysical problem, but also as a production, market, and decision-making challenge (Petersen-Rockney, 2022). In different regions, climate change has been associated with risks to crop production, food security, and the stability of agricultural supply chains (Reza and Sabau, 2022). For livestock systems, this reinforces the importance of reducing uncertainty in emission estimates and identifying management practices that can improve production while reducing accumulated emissions.

Livestock production is particularly sensitive to climate variability because animal performance depends on pasture productivity, forage quality, water availability, thermal comfort, and reproductive efficiency (Cheng et al., 2022). Public debate on animal agriculture and climate change has also increased pressure for more transparent emission accounting and clearer mitigation pathways (Kristiansen; Painter and Shea, 2021). In regions exposed to drought, rainfall variability, or extreme climatic events, livestock productivity can be reduced, increasing the time required for animals to reach adequate slaughter weight (Bogale and Erena, 2022; Warsame et al., 2022). This mechanism is consistent with the present results, because longer animal retention time increased the importance of adult males in the Tier 2 emission profile.

The effect of climate on animal production has also been documented in dairy systems, where heat stress and reduced feed availability can affect performance, welfare, and reproductive responses (Bhakat et al., 2023). Although the present study focused on male buffaloes, these broader findings are relevant because buffalo production in Pará occurs under tropical conditions where pasture seasonality, heat load, and management limitations may affect animal growth. Therefore, the greater contribution of animals older than 36 months to Tier 2 emissions should be interpreted as a demographic signal associated with productive efficiency and animal retention time.

Official livestock data are essential for interpreting these emission patterns at territorial scale. National livestock statistics provide the broader context of herd distribution and production dynamics in Brazil (IBGE, 2024). In the Amazon, buffalo production has specific territorial importance, especially in areas where the species is adapted to humid environments and extensive grazing systems (Lourenço-Júnior and Garcia, 2008). Extensive systems in the Brazilian Amazon may include low infrastructure, limited herd control, and strong dependence on natural or low-managed pastures (Franco et al., 2023). These characteristics help explain why the age structure of the herd becomes a decisive factor in the interpretation of enteric CH_4 emissions in Pará.

Studies conducted in the Amazon have shown that buffaloes and cattle respond strongly to environmental conditions, including solar radiation, shade availability, heat load, and seasonal climate patterns (Silva et al., 2022; Silva et al., 2022). Animal welfare and reproductive performance are also influenced by thermal stress and management conditions (Silva, et al., 2023a). The temperature and humidity index has been used to support decisions on ruminant production systems in Amazonian environments, showing that climate conditions can affect the feasibility and efficiency of different rearing strategies (Silva, et al., 2023b). These findings are consistent with the present interpretation that low productive efficiency can prolong the production cycle and increase accumulated CH_4 emissions.

Thermal pattern assessments and thermolytic responses in cattle reared in the Eastern Amazon indicate that production systems differ in their capacity to buffer climatic stress (Silva, et al., 2023a). In buffaloes, studies on thermal biology in humid tropical conditions show that physiological and behavioral responses are important for understanding adaptation and productivity (Mota-Rojas et al., 2021). Behavioral studies in dairy buffaloes also reinforce that management, calving, maternal behavior, and social interactions influence productive performance (Mota-Rojas et al., 2022). Therefore, the emission pattern observed in this study should not be interpreted only as a mathematical result of herd size, but as a response to a production system in which environment, management, and animal biology interact.

Reviews on water buffalo production systems show that behavior, productivity, and breeding conditions vary widely according to management intensity, environmental conditions, and production goals (de la Cruz-Cruz et al., 2014). Reproductive and behavioral responses in buffalo cows also show that physiological status and management quality influence herd performance (González-Lozano et al., 2020). In addition, the human-animal relationship can affect productivity and welfare, which may indirectly influence growth rate, handling efficiency, and the time animals remain in the production system (Mota-Rojas et al., 2020). These references support the interpretation that reducing adult male retention requires not only better pastures, but also improved herd management and zootechnical control.

The atypical accumulation of animals older than 36 months in 2010 and 2011 may also be interpreted in relation to sanitary and market conditions. Sanitary restrictions associated with foot-and-mouth disease have affected livestock commercialization in Brazil and may alter the timing of animal sale, movement, and slaughter (MAPA, 2020). Livestock production cycles also influence the retention and replacement of animals on farms, because market prices and herd rebuilding strategies affect producer decisions (AIA, 2024). Therefore, the red cluster identified in the multivariate analysis, represented by 2010 and 2011, may reflect not only biological age structure, but also external constraints that delayed animal removal from the production system.

The comparison with methane studies in buffaloes and cattle strengthens the biological interpretation of the Tier 2 results. Nutritional strategies using essential oils in growing buffaloes have shown that diet composition can affect methane production, growth, and nutrient utilization (Yatoo et al., 2017). Seasonal measurements of CH_4 emissions from grazing cattle also show that pasture conditions and climate seasonality influence enteric methane dynamics (Demarchi et al., 2016). Methodological comparisons using methane hoods and respiration chambers demonstrate that measurement technique can affect CH_4 estimates, which reinforces the need to interpret inventory-based values in relation to method and production context (Troy et al., 2016).

The role of diet and by-products is also relevant for interpreting mitigation pathways. Studies using biodiesel by-products in cattle diets show that alternative feed resources can modify intake behavior and physiological parameters (Correia et al., 2012). This is important for Pará because agricultural by-products and supplementation strategies may help improve nutrient supply during periods of low pasture quality. If supplementation increases weight gain and reduces the time required for animals to reach market weight, it can reduce the cumulative period during which animals emit CH_4 in pasture-based systems.

Mitigation strategies for ruminant methane emissions include dietary manipulation, feed additives, improved forage quality, better animal performance, and increased production efficiency (Króliczewska; Pecka-Kiełb and Bujok, 2023). However, such strategies must be interpreted with caution because their effectiveness depends on production system, animal category, diet, adoption conditions, and regional feasibility. The present study contributes to this debate by showing that, in addition to reducing emission factors, managing herd age structure is also a relevant mitigation pathway. In Pará, avoiding prolonged retention of adult males can reduce the contribution of the > 36-month category to total Tier 2 emissions.

Climate impacts on crop production also affect livestock systems indirectly because feed availability depends on agricultural productivity and climatic stability (Streck and Alberto, 2006). Reduced performance of forage crops, grains, or supplementary feed sources can compromise animal nutrition, delay finishing, and increase residence time on farms. This connection reinforces the need to integrate livestock emission accounting with broader food-system planning, especially in regions where pasture-based production supports both domestic supply and export potential.

Overall, the literature supports the central finding of this study: enteric CH_4 emissions from male buffaloes in Pará cannot be interpreted only by total herd size. The Tier 2 approach revealed that age-class composition, especially the retention of animals older than 36 months, changed the emission profile of the herd. The multivariate analyses confirmed that 2010 and 2011 formed an adult-retention profile, while recent high-emission years reflected herd expansion. Therefore, mitigation strategies should prioritize better pasture management, nutritional improvement, zootechnical control, and animal removal before or around 36 months of age, allowing buffalo production systems to improve productive efficiency while reducing accumulated CH_4 emissions.

5. Conclusions

This study demonstrated that enteric CH_4 emissions from male buffaloes in Pará were influenced not only by total herd size, but also by changes in herd age-class composition. The Tier 1 approach provided a broad estimate of emissions based on a fixed emission factor and allowed the evaluation of the long-term historical series. However, because this approach applies the same emission factor to all animals, it mainly reflected changes in herd population.

The Tier 2 approach provided a more refined interpretation by incorporating age-specific emission factors. Animals older than 36 months showed the highest emission factor within the Tier 2 structure and contributed most to total Tier 2 CH_4 emissions. The correlation analysis, principal component analysis, and cluster analysis consistently showed that years with higher emissions, especially 2010, 2011, and 2021, were associated with greater retention of adult male buffaloes in the herd.

These results confirm that animal retention time is a key factor in accumulated enteric methane emissions. Therefore, mitigation strategies for buffalo production systems in the eastern Amazon should prioritize productive efficiency, pasture recovery, forage quality, nutritional management, zootechnical control, and earlier animal removal from farms. Reducing the proportion of males retained beyond 36 months can shorten the production cycle, decrease accumulated CH_4 emissions, and improve the environmental performance of pasture-based buffalo production in Pará.

By linking herd structure, age-specific emission factors, and multivariate analysis, this study provides a regional contribution to livestock GHG accounting. The results reinforce the need to use more detailed and regionally consistent approaches in inventories, especially for species and production systems that remain less represented in national emission assessments.

Authors' contribution

Vinícius Costa Gomes de Castro: Conceptualization, Methodology, Data curation, Validation, Formal analysis, Writing – Original draft. Lucietta Guerreiro Martorano: Conceptualization, Methodology, Software, Data Curation, Formal analysis, Validation, Supervision, Funding acquisition, Project administration. Jamile Andréa Rodrigues da Silva: Conceptualization, Methodology, Visualization, Writing – Review & Edting. Natália Guarino Sousa Barbosa: Writing – Review & Edting. José Reinaldo da Silva Cabral de Moraes: Methodology, Data curation. João Maria do Amaral Júnior: Visualization, Writing – Review & Edting. Paulo Campos Christo Fernandes: Validation, Visualization, Writing – Review & Edting. Welligton Conceição da Silva: Methodology, Data curation, Formal analysis, Validation, Writing – Original draft. Thomaz Cyro Guimarães de Carvalho Rodrigues: Formal analysis, Data curation, Visualization, Writing – Review & Edting. Éder Bruno Rebelo da Silva: Formal analysis, Data curation, Writing – Review & Edting. Leonel António Joaquim: Data curation, Visualization, Validation, Writing – Original draft. Laíza de Kássia Mendes Conceição: Writing – Original draft, Writing – Review & Edting. Mariana Jucá Moraes: Writing – Original draft, Writing – Review & Edting. Patricia Perondi Anchão Oliveira: Validation, Visualization, Writing – Review & Edting. Anna Patrycia Martins de Oliveira: Writing – Original draft, Writing – Review & Edting. João Vitor da Silva Oliveira: Writing – Original draft, Writing – Review & Edting. José de Brito Lourenço Júnior: Conceptualization, Methodology, Supervision, Resources, Project administration.

Declarations

Conflicts of Interest

The authors have no competing interests to declare that are relevant to the content of this article.

Funding

This study was funded in part by the Federal University of Pará, the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, CAPES, and Brazilian National Council for Scientific and Technological Development, CNPq, through a Research Productivity Fellowship, grant number 305359/2025-8.

Author Contribution

V.C.G.C. Conceptualization, Methodology, Data curation, Validation, Formal analysis, Writing – Original draft. L.G.M. Conceptualization, Methodology, Software, Data Curation, Formal analysis, Validation, Supervision, Funding acquisition, Project administration. J.A.R.S. Conceptualization, Methodology, Visualization, Writing – Review & Edting. N.G.S.B. Writing – Review & Edting. J.R.S.CM. Methodology, Data curation. J.M.A.J. Visualization, Writing – Review & Edting. P.C.C.F. Validation, Visualization, Writing – Review & Edting. W.C.S.: Methodology, Data curation, Formal analysis, Validation, Writing – Original draft. T.C.G.C.R. Formal analysis, Data curation, Visualization, Writing – Review & Edting. É.B.R.S. Formal analysis, Data curation, Writing – Review & Edting. L.A.J. Data curation, Visualization, Validation, Writing – Original draft. L.K.M.C. Writing – Original draft, Writing – Review & Edting. M.J.M. Writing – Original draft, Writing – Review & Edting. P.P.A.O. Validation, Visualization, Writing – Review & Edting. A.P.M.O. Writing – Original draft, Writing – Review & Edting. J.V.S.O. Writing – Original draft, Writing – Review & Edting. J.B.L.J. Conceptualization, Methodology, Supervision, Resources, Project administration.

Acknowledgement

The authors thank Embrapa Amazônia Oriental for institutional and technical support during the development of this study. Special acknowledgment is given to the Rede PECUS and to Project Component 7, Assessment of Greenhouse Gases in the Amazon Biome, which supported scientific advances on greenhouse gas dynamics in Amazonian agricultural and livestock systems. The authors also thank UFRA/PPGSPAA, UFPA/PPGCAN, and the Agriculture and Livestock Defense Agency of the State of Pará, ADEPARÁ, for institutional collaboration and for providing the herd database used in this study. The authors acknowledge CAPES and CNPq for supporting graduate and undergraduate students involved in this research.

Data Availability

All data supporting the findings of this study are available within the paper.

References

1. Abegunde, V. O., Sibanda, M. & Obi, A. The Dynamics of Climate Change Adaptation in Sub-Saharan Africa: A Review of Climate-Smart Agriculture among Small-Scale Farmers. *Clim. 2019*. **7** (11), 132. https://doi.org/10.3390/CLI7110132 (2019). *7*.
2. Adedeji, O., Reuben, O. & Olatoye, O. Global Climate Change. *J. Geoscience Environ. Prot.* **02** (02), 114–122. https://doi.org/10.4236/GEP.2014.22016 (2014).
3. Ahmed, M., Asim, M., Ahmad, S. & Aslam, M. Climate Change, Agricultural Productivity, and Food Security. *Global Agricultural Production: Resilience to Climate Change*, 31–73. (2023). https://doi.org/10.1007/978-3-031-14973-3_2/SAVE-RESEARCH
4. AIA. Avaliação dos Dados de Captação, Industrialização do Leite e do Abate de Vacas no Brasil e estado de São Paulo, em 2023. *Análises e Indicadores do Agronegócio*, *19*(5). (2024). https://sidra.ibge.gov.br/home/leite/brasil
5. Aryal, J. P. et al. Climate change and agriculture in South Asia: adaptation options in smallholder production systems. *Environ. Dev. Sustain.* **2019 22:6** (6), 5045–5075. https://doi.org/10.1007/S10668-019-00414-4 (2019). *22*.
6. Azadi, H. et al. Climate Smart Agriculture: Mitigation and Adaptation Strategies at the Global Scale. *Climate-Induced Innov.* 81–140. https://doi.org/10.1007/978-3-031-01330-0_4 (2022).
7. Bhakat, M., Maiti, S., Mondal, G., Mohanty, T. K. & Ragulraj, S. Impact of climate change on dairying in India and resilient strategies with available technological options. Em S. Maiti, S. Garai, A. Panja, S. Zade, B. Meena, & G. Sankhala (Orgs.), *Social Science Dimensions of Climate Resilient Agriculture* (pp. 15–37). ICAR-National Dairy Research Institute. (2023). https://www.researchgate.net/profile/Sanjit-Maiti/publication/372909405_Social_Science_Dimensions_of_Climate_Resilient_Agriculture/links/64cd3c4191fb036ba6c6d311/Social-Science-Dimensions-of-Climate-Resilient-Agriculture.pdf
8. Bogale, G. A. & Erena, Z. B. Drought vulnerability and impacts of climate change on livestock production and productivity in different agro-Ecological zones of Ethiopia. *J. Appl. Anim. Res.* **50** (1), 471–489. https://doi.org/10.1080/09712119.2022.2103563 (2022).
9. Bolson, S. H. & de Araújo, S. F. As Metas Brasileiras ao Acordo de Paris sobre as Mudanças Climáticas. *RELPE* **5** (1), 144–148 (2022). https://sistemas.uft.edu.br/periodicos/index.php/relpe/article/download/14502/20175/64940
10. Cheng, M., McCarl, B. & Fei, C. Climate Change and Livestock Production: A Literature Review. *Atmos. 2022*. **13** (1), 140. https://doi.org/10.3390/ATMOS13010140 (2022). *13*.
11. Correia, B. R. et al. Comportamento ingestivo e parâmetros fisológicos de novilhos alimentados com tortas do biodiesel. *Arch. de Zootecnia*. **61** (233), 79–89. https://doi.org/10.4321/S0004-05922012000100009 (2012).
12. de la Cruz-Cruz, L. A. et al. The behaviour and productivity of water buffalo in different breeding systems: a review. https://vetmed.agriculturejournals.cz/doi/10.17221/7479-VETMED.*html, 59*(4), 181–193. (2014). https://doi.org/10.17221/7479-VETMED
13. Demarchi, J. J. A. A. et al. Effect of Seasons on Enteric Methane Emissions from Cattle Grazing Urochloa brizantha. *J. Agric. Sci.* **8** (4), 106. https://doi.org/10.5539/JAS.V8N4P106 (2016).
14. Estevão, C. G., de Pavão, E. & Assad, E. D. M., *Quantificação das Emissões de GEE no Setor Agropecuário: Fatores de Emissão, Métricas e Metodologias*. Observatório de Conhecimento e Inovação em Bioeconomia, Fundação Getulio Vargas. (2023). https://agro.fgv.br/sites/default/files/2023-10/M%C3%A9tricas%20Agropecu%C3%A1rias.pdf
15. Franco, D. L., Silva, F. P., Maciel, J. C. T. & Vital, T. W. Abordagem metodológica para análise de manejo comunitário de fauna em sistema extensivo na Amazônia brasileira. *Desenvolvimento e Meio Ambiente*. **61**, 18–31. https://doi.org/10.5380/DMA.V61I0.79108 (2023).
16. Gavrilova, O. et al. K., Emissions from livestock and manure management. Em *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Vol. 4, p. 10.1-10.207). IPCC. (2019).
17. Genro, T. C. M., de Lara, D. M. & Lamperti, V. do N. Analise das emissoes de metano enterico do rebanho de bovinos de corte do Rio Grande do Sul. *Embrapa, Comunicado Técnico 109*, 12. (2023)., novembro https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1158126/1/CT-109-Online.pdf
18. González-Lozano, M. et al. Review: Behavioral, physiological, and reproductive performance of buffalo cows during eutocic and dystocic parturitions. *Appl. Anim. Sci.* **36** (3), 407–422. https://doi.org/10.15232/AAS.2019-01946 (2020).
19. IBGE. *Produção da pecuária municipal 2023*. (2024).
20. Jiao, H., Yan, T., Wills, D. A., Carson, A. F. & McDowell, D. A. Development of prediction models for quantification of total methane emission from enteric fermentation of young Holstein cattle at various ages. *Agric. Ecosyst. Environ.* **183**, 160–166. https://doi.org/10.1016/J.AGEE.2013.11.004 (2014).
21. Kristiansen, S., Painter, J. & Shea, M. Animal Agriculture and Climate Change in the US and UK Elite Media: Volume, Responsibilities, Causes and Solutions. *Environ. Communication*. **15** (2), 153–172. https://doi.org/10.1080/17524032.2020.1805344 (2021).
22. Króliczewska, B., Pecka-Kiełb, E. & Bujok, J. Strategies Used to Reduce Methane Emissions from Ruminants: Controversies and Issues. *Agric. 2023*. **13** (3), 602. https://doi.org/10.3390/AGRICULTURE13030602 (2023). *13*.

23. Lanzoni, L. et al. Assessment of Seasonal Variation in Methane Emissions of Mediterranean Buffaloes Using a Laser Methane Detector. *Anim. 2022*. **12** (24), 3487. https://doi.org/10.3390/ANI12243487 (2022). *12*.
24. Lima, M. T. D., Macedo, L. O. B. & Vignandi, R. S. Valoração das emissões de GEE oriundas de desmatamento na Bacia do Rio São Lourenço, Mato Grosso, Brasil. *Revista em Agronegócio e Meio Ambiente*. **16** (4), 199. https://doi.org/10.17765/2176-9168.2023V16N4E11390 (2023).
25. de Lourenço-Júnior, J. & Garcia, A. R. B., *Panorama da Bubalinocultura na Amazônia*. (2008). https://www.alice.cnptia.embrapa.br/alice/bitstream/doc/409969/1/LOURENCO2008AmazonpecPanorama.pdf
26. Malla, F. A. et al. Understanding Climate Change: Scientific Opinion and Public Perspective. *Clim. Change: Social Sci. Construct*. 1–20. https://doi.org/10.1007/978-3-030-86290-9_1/SAVE-RESEARCH (2022).
27. MAPA. *Vigilância para a Febre Aftosa* (1º ed). Ministério da Agricultura, Pecuária e Abastecimento. (2020). http://www.adab.ba.gov.br/wp-content/uploads/Plano_12951936_Plano_de_Vigilancia_para_Febre_Aftosa_1a_Edicao_2020-1.pdf
28. Martorano, L. G. et al. Agricultural and livestock production in the Amazon: A reflection on the necessity of adoption of integrated production strategies in the western region of the state of Para. *Aust. J. Crop Sci.* **15**, 1102–1109. https://search.informit.org/doi/abs/10.3316/informit.179690707250399# (2021).
29. Mbow, C. et al. Food security. *Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, 437–550. (2022). https://doi.org/10.1017/9781009157988.007
30. MCT. *3ª Comunicação Nacional do Brasil à Convenção-Quadro das Nações Unidas sobre Mudança do Clima*. (2016). https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/sirene/publicacoes/comunicacoes-nacionais-do-brasil-a-unfccc/arquivos/3tcn_volume_3.pdf
31. MCT. *Relatório do Inventário Nacional das Emissões Antrópicas por Fontes e das Remoções por Sumidouros de Gases de Efeito Estufa do Brasil - Primeiro Relatório bienal de Transparência à Convenção-Quadro das Nações Unidas Sobre Mudança do Clima*. (2024).
32. Meehl, G. A. et al. The WCRP CMIP3 Multimodel Dataset: A New Era in Climate Change Research. *Bull. Am. Meteorol. Soc.* **88** (9), 1383–1394. https://doi.org/10.1175/BAMS-88-9-1383 (2007).
33. Mota-Rojas, D. et al. Dairy Buffalo Behavior: Calving, Imprinting and Allosuckling. *Anim. 2022*. **12** (21), 2899. https://doi.org/10.3390/ANI12212899 (2022). *12*.
34. Mota-Rojas, D. et al. Effects of human-animal relationship on animal productivity and welfare. *J. Anim. Behav. Biometeorol.* **8** (3), 196–205. https://doi.org/10.31893/JABB.20026 (2020).
35. Mota-Rojas, D. et al. Thermal biology in river buffalo in the humid tropics: neurophysiological and behavioral responses assessed by infrared thermography. *J. Anim. Behav. Biometeorol.* **9** (1), 2103–2103. https://doi.org/10.31893/JABB.21003 (2021).
36. Petersen-Rockney, M. Social risk perceptions of climate change: A case study of farmers and agricultural advisors in northern California. *Glob. Environ. Change*. **75**, 102557. https://doi.org/10.1016/J.GLOENVCHA.2022.102557 (2022).
37. Plattner, G. K., Stocker, T., Midgley, P. & Tignor, M. *IPCC Expert Meeting on the Science of Alternative Metrics Meeting Report*. (2009). http://www.ipcc.ch/
38. Praveen, B. & Sharma, P. A review of literature on climate change and its impacts on agriculture productivity. *Journal of Public Affairs*, *19*(4), e1960. (2019). https://doi.org/10.1002/PA.1960;REQUESTEDJOURNAL:JOURNAL:14791854;WGROUP:STRING:PUBLICATION.
39. Reza, M. S. & Sabau, G. Impact of climate change on crop production and food security in Newfoundland and Labrador, Canada. *J. Agric. Food Res.* **10**, 100405. https://doi.org/10.1016/J.JAFR.2022.100405 (2022).
40. Silva, J. A. R. et al. A. V. C., J. de B. Thermoregulatory reactions of female buffaloes raised in the sun and in the shade, in the climatic conditions of the rainy season of the Island of Marajó, Pará, Brazil. *Frontiers in Veterinary Science*, *9*, 998544. (2022). https://doi.org/10.3389/FVETS.2022.998544/TEXT
41. da Silva, W. C. et al. da, dos, e.,& J. de B. Evaluation of the temperature and humidity index to support the implementation of a rearing system for ruminants in the Western Amazon. *Frontiers in Veterinary Science*, *10*, 1198678. (2023). https://doi.org/10.3389/FVETS.2023.1198678/TEXT
42. da Silva, W. C. et al. Behavior and thermal comfort of light and dark coat dairy cows in the Eastern Amazon. *Front. Veterinary Sci.* **9**, 1006093. https://doi.org/10.3389/FVETS.2022.1006093/TEXT (2022). & Lourenço Júnior, J. de B
43. da Silva, W. C. et al. e., da, J. de B. Animal welfare and effects of per-female stress on male and cattle reproduction—A review. *Frontiers in Veterinary Science*, *10*, 1083469. (2023a). https://doi.org/10.3389/FVETS.2023.1083469/FULL
44. da Silva, W. C. et al. Characterization of Thermal Patterns Using Infrared Thermography and Thermolytic Responses of Cattle Reared in Three Different Systems during the Transition Period in the Eastern Amazon, Brazil. *Anim. 2023*. **13** (17), 2735.

https://doi.org/10.3390/ANI13172735 (2023b). *13*.

45. Streck, N. A. & Alberto, C. M. Estudo numérico do impacto da mudança climática sobre o rendimento de trigo, soja e milho. *Pesquisa Agropecuária Brasileira*. **41** (9), 1351–1359. https://doi.org/10.1590/S0100-204X2006000900002 (2006).
46. Troy, S. M. et al. A comparison of methane emissions from beef cattle measured using methane hoods with those measured using respiration chambers. *Anim. Feed Sci. Technol.* **211**, 227–240. https://doi.org/10.1016/J.ANIFEEDSCI.2015.12.005 (2016).
47. Warsame, A. A., Sheik-Ali, I. A., Hassan, A. A. & Sarkodie, S. A. Extreme climatic effects hamper livestock production in Somalia. *Environ. Sci. Pollution Res. 2021*. **29:27** (27), 40755–40767. https://doi.org/10.1007/S11356-021-18114-W (2022). *29*.
48. WRI Brasil. *Metodologia do GHG Protocol da agricultura*. (2015). https://ghgprotocol.org/sites/default/files/2022-12/Metodologia.pdf
49. Xue, B., Wang, L. Z. & Yan, T. Methane emission inventories for enteric fermentation and manure management of yak, buffalo and dairy and beef cattle in China from 1988 to 2009. *Agric. Ecosyst. Environ.* **195**, 202–210. https://doi.org/10.1016/J.AGEE.2014.06.002 (2014).
50. Yatoo, M. A., Chaudhary, L. C., Agarwal, N., Chaturvedi, V. B. & Kamra, D. N. Effect of feeding of blend of essential oils on methane production, growth, and nutrient utilization in growing buffaloes. *Asian-Australasian J. Anim. Sci.* **31** (5), 672. https://doi.org/10.5713/AJAS.16.0508 (2017).

Figures

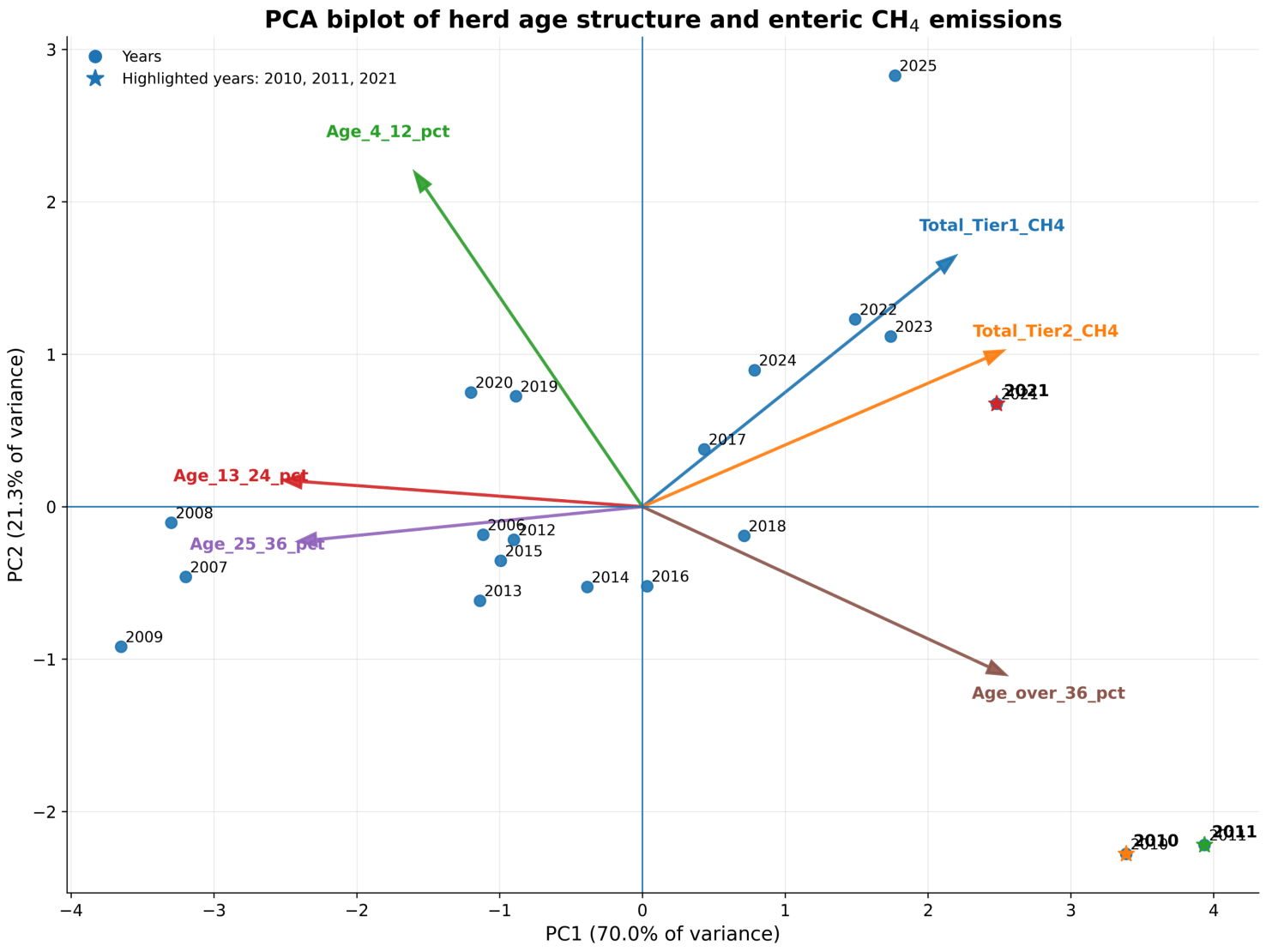


Figure 1

Principal component analysis biplot showing the relationship between herd age-class composition and enteric CH_4 emissions estimated using Tier 1 and Tier 2 approaches for male buffaloes in Pará, eastern Amazon, Brazil, from 2006 to 2025. Vector colors distinguish age classes and total emissions estimated by Tier 1 and Tier 2

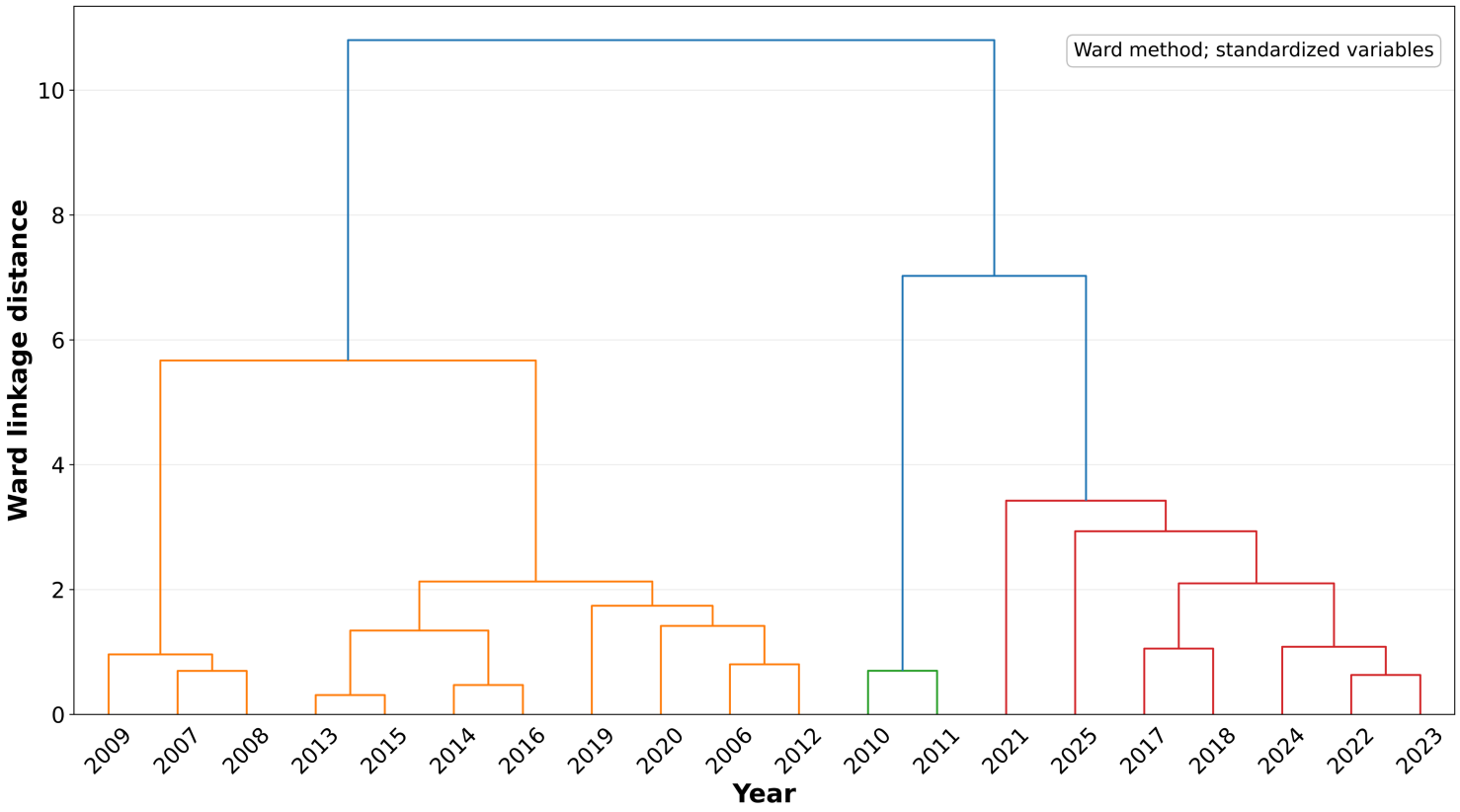


Figure 2

Hierarchical clustering dendrogram of years based on herd age-class composition and enteric CH_4 emissions estimated using Tier 1 and Tier 2 approaches for male buffaloes in Pará, eastern Amazon, Brazil, from 2006 to 2025. Clustering was performed using standardized variables, Euclidean distance, and Ward's linkage method

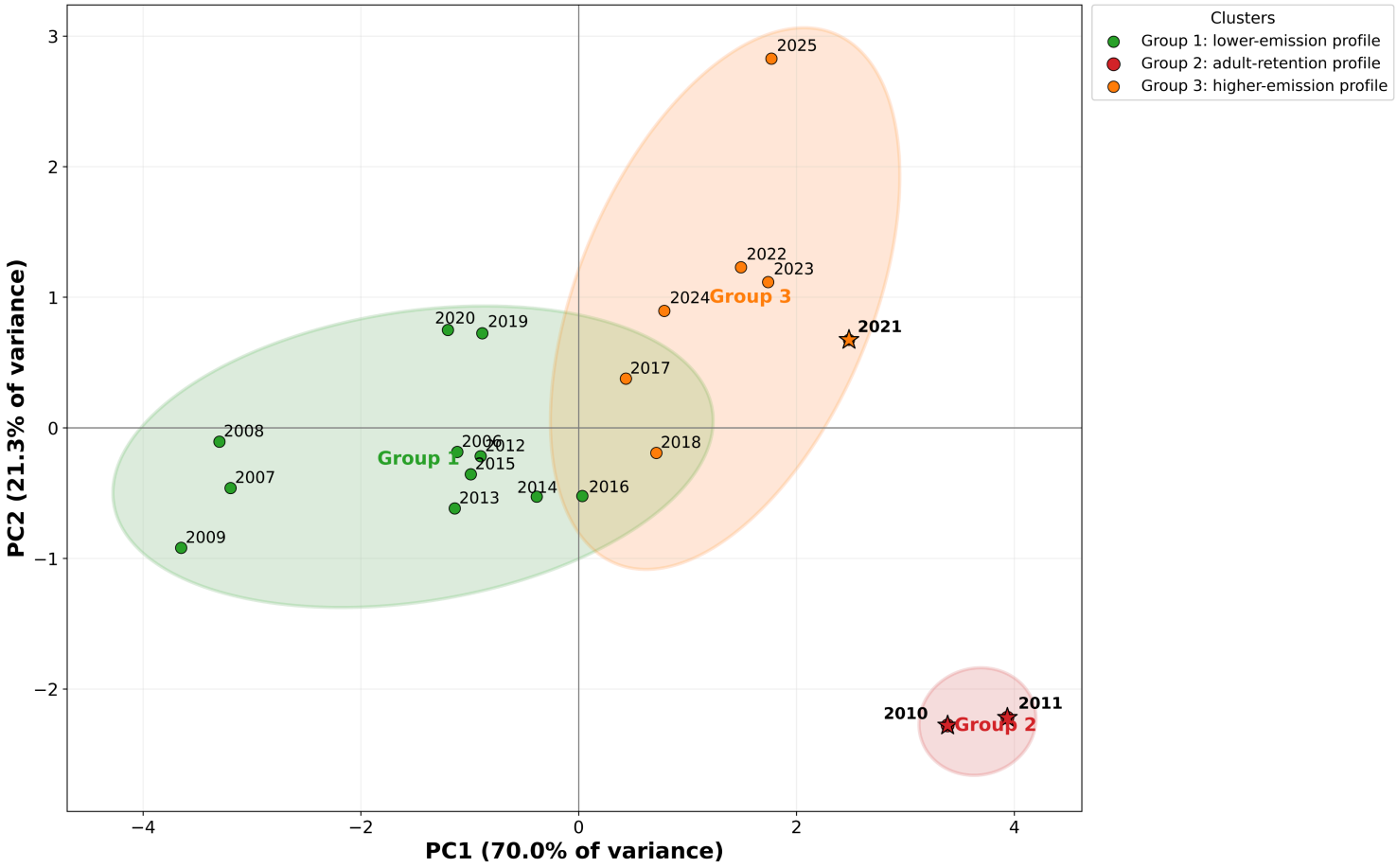


Figure 3

Cluster projection of years onto the PCA space based on herd age-class composition and enteric CH_4 emissions estimated using Tier 1 and Tier 2 approaches for male buffaloes in Pará, eastern Amazon, Brazil, from 2006 to 2025. Green indicates years with lower emission profiles, red indicates years characterized by adult animal retention, and orange indicates years with higher emission profiles