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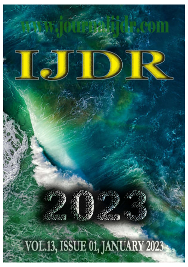

RESEARCH ARTICLE **OPEN ACCESS**

ENVIRONMENTAL EFFICIENCY OF BRAZILIAN LIVESTOCK FARMING: A REGIONAL GREENHOUSE GAS EMISSIONS APPROACH

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ABSTRACT

This article aims to establish a survey of CO2e (t GWP) emissions and carbon sequestration in Brazilian livestock. The study considers CO_2, CH_4, N_2O as GHG, being presented in carbon equivalent (CO_2eq) in the metric GWP (global warming potential). Based on data from Greenhouse Gas Emission and Removal Estimating System, an estimate of carbon removals in the soil due to agricultural practices was included in an experimental way. The assessment of GHG emissions from livestock over time and geographic space is essential so that mitigation measures are created, adopted and disseminated properly. Two indices were analyzed: Relative Herd Emissions Index (HREI) and Relative Carcass Emissions Index (CREI). From 1997 to 2019, Brazil increased its effective herd by 33.13%, gross GHG emissions by 31.62%, carbon sequestration by 91.20% and carcass weight by 146.45%. The zootechnical indices of beef cattle systems have improved over the years, reflecting the issues of environmental efficiency captured in the negative variations of the HREI and CREI indices. Net GHG emissions per animal (beef cattle) were reduced by -10.90%, while per kilogram of beef was produced by -51.81%.We demonstrate that the indicators used regionally can help as an alternative tool for the elaboration of national inventories and policy definitions aimed at the productive sector. For countries with a large territorial extension, different biomes and different livestock management, the identification of specific regional indexes bring precision to support scientific studies and governmental decisions that link regional development and the environment.

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INTRODUCTION

The sustainability of Brazilian livestock farming is a recurring theme in global agribusiness discussions. Brazil is the fifth largest country in the world with a land area of 8.5 million km², of which it has approximately 209 thousand hectares of pastureland, about 21% of the territory (Ferraz e Felício, 2010; Eri *et al*., 2020; Oliveira *et al*., 2020). This expanse of land is spread over different areas and regions with variations in temperature, humidity, relief and biomes (Souza Jr *et al*., 2020). Brazil has the largest commercial cattle herd in the world, raised in different production systems and animal densities. Depending on the region, production systems can vary between extensive (in which animals feed freely in natural or cultivated pastures), semi-intensive (where animals remain confined part-time and free, receiving voluminous feed supplements or concentrates) and intensive (where animals are confined and fed exclusively with products, such as grains, or co-products) (McManus, *et al*., 2016; Cardoso *et al*., 2020). The country also stands out for the use of technological innovations in genetic improvement, nutrition and production systems. These technologies allow for greater productivity, increased beef production per land area, and a shorter production cycle (Cottle & Kahn, 2014; Lobato *et al*., 2014). These characteristics, together with the almost total dependence on pasture and low production costs, make Brazilian livestock farming highly competitive and important in the world (Costa *et al*., 2018; Veloso *et al*., 2020). Brazil is considered an important player on the international stage, both for its contribution to food security and for its share in global GHG emissions (Ferraz e Felício, 2010; Cardoso *et al*., 2020). On the other hand, cattle production has drawn international attention for the frequent questions about production practices and environmental impacts attributed to Brazilian cattle farming (Olausson, 2018). This situation has become central in the discussion of measures to mitigate GHG emissions (Godfray, 2015, Cardoso *et al*., 2020). In this regard, several studies on the levels of GHG emissions in different production systems have been carried out in Brazil and worldwide (Tongwane *et al*., 2016; Dimitrov e Wang, 2019; Kumari *et al*., 2019). The increasing concentration of GHGs in the atmosphere has been identified as one of the main causes of global warming, with carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O) being the main long-lived GHGs (Meinshausen *et al*, 2011). The challenge of promoting food security for a growing population is linked to the need to establish production systems with low environmental externalities and resilience to climate change (Godfray, 2015; Cardoso *et al*., 2020). Livestock, agriculture, land use and forestry are responsible for almost one-third of total GHG emissions, generated mainly by enteric fermentation and manure left on land and pasture (Tubiello *et al*., 2014). A relevant aspect of the Brazilian GHG emissions concerns the emissions profile and the method used to quantify them (Azevedo *et al*., 2018).

In a country with five biomes, diverse climates and environmental conditions, estimating the amount of GHG emitted by enteric fermentation, dealing with animal wastes and agricultural soils becomes a complex task (Souza Jr. *et al*., 2020; Veloso *et al*., 2020). Even so, it is necessary to advance the analysis of GHG emission patterns in space and time. In this sense, quantifying GHG emissions by specific geographic areas can help policy makers in mitigation, using a local or regional zoning perspective. Despite the challenge of continuously increasing beef production, Brazil is committed to reducing deforestation and GHG emissions in accordance with the commitments recorded in the NDCs proposed by the country in the Paris Agreement (NFCCC, 2021). Sustainable intensification is a process designed to achieve higher agricultural yields whilst simultaneously reducing the negative impact of farming on the environment (Godfray, 2015). In this sense, the present paper aims, firstly, to establish a spatially distributed long-term balance for GHG emissions in the productive stage of Brazilian cattle ranching by regional zoning; and, secondly, to analyze the efficiency in net GHG emissions and their performance in space and time.

MATERIAL AND METHODS

Description of the study and data: Faced with concerns about animal production's ecological footprint, studies that evaluate the efficiency of the production systems become essential. As a continental country, Brazil has a distinct characteristic between its regions in terms of climate, biome, relief, soil and management practices of production systems. These are the reasons why we intend to assess total and net GHG emissions over time and in geographic space, seeking to analyze the efficiency of livestock systems by Brazilian states and regions. The assessment was carried out using two indices: Herd Relative Emissions Index (HREI) and Carcass Relative Emissions Index (CREI), described in the following section. The data used in the analysis refer to gross GHG emissions, net GHG emissions, effective beef cattle herd and carcass weight. The study considers CO_2, CH_4, N_2O as GHG, being presented in carbon equivalent (tCO_2eq) according to their global warming potential (GWP). The data converted to tCO_2eq were accessed from the Greenhouse Gas Emission and Removal Estimating System – (SEEG, 2021), where the soil carbon removals due to agricultural practices were estimated based on experimental data (Table 1). The data are aggregated for Brazil and disaggregated by state and Federal District (Table 2).

Description of the indices: To measure GHG emissions' efficiency from beef cattle, the relative efficiency indices of each state and region were analyzed. The net GHG emissions (NE) was determined by the difference between gross GHG emissions (GE) and carbon sequestration (CS) (Equation 1). The Herd Relative Emission Index (HREI) is obtained by dividing net GHG emissions by the effective herd (EH) (Equation 2). HREI was analyzed over a 30-year time series from 1990 to 2019. The Carcass Relative Emission Index (CREI) is obtained by dividing net GHG emissions by the carcass weight (CW) (Equation 3). The index was analyzed for a time series covering the years 1997 to 2019. CREI was analyzed in a 23-year time series from 1997 to 2019, depending on data availability.

$$NE = GE - CS \qquad \text{(Eq. 1)}$$

$$REI = \frac{Net\ GHG\ Emissions}{EH} \qquad \text{(Eq. 2)}$$

$$CREI = \frac{Net\ GHG\ Emissions}{CW} \qquad \text{(Eq. 3)}$$

GHG emissions from livestock are related to enteric fermentation, animal manure management and agricultural soils. The Brazilian GHG inventory does not consider emissions and carbon sequestration in the soil by agricultural practices. As the accounting for both emissions and removals is essential to assess the goals proposed by Brazilian NDCs, SEEG (2021) presents the calculations of carbon emissions and removals according to the quality of pasture, adoption of no-till practices, forest plantations and crop-livestock-forest integration. These data are used to calculate the net GHG emissions.

Data analysis: The data were analyzed in four steps: 1) evaluation of total GHG emissions by animal category in the period from 1970 to 2019; 2) participation of the emission processes in the total GHG emissions during the period from 1970 to 2019; 3) correlation between the variables HREI, CREI, net emissions, carcass weight and cattle herd; 4) analysis of variance (Equation 4) and grouping states and regions by proximity in the GHG emissions efficiency (Equation 5).

$$F_{(g-1,N-g)} = \frac{QMTr}{QMR} \qquad \text{(Eq. 4)}$$

where:

$QMTr$ = mean square of treatment;
QMR = mean square of residues;
g = number of groups; and,
N = sample size

$$DMS_{Scheff\acute{e}} = \sqrt{(t-1) \times F \times V} \qquad \text{(Eq. 5)}$$

where:

t = number of treatments;
F = tabulated F-value for (t-1) and GL (degrees of freedom); and,
V = contrast variance

Methodological notes: It is worth noting that the data regarding gross and net GHG emissions are not differentiated by intensive and extensive livestock systems. However, it is possible to qualify the analysis through secondary data available in studies applied in the states and regions where those livestock systems predominate (Carvalho,2021; Cezimbra, 2021; Lobato *et al*., 2014; McManus, *et al*., 2016; Godfray, 2015; Jaurena *et al*., 2021). The results configure an analysis of efficiency indices in a spatial and temporal perspective, reflecting structural trends in the sector concerning GHG emissions.

RESULTS AND DISCUSSION

GHG emissions in perspective: Animal production contributes directly and indirectly to a portion of the environmental impact (positive or negative) caused by GHG emissions. The Intergovernmental Panel on Climate Change (IPCC) lists some GHGs emitting species according to what we present in Figure 1. In that way, we grouped the animal species into emitting groups. As shown in Table 3, pigs and cattle have been the groups responsible for most GHG emissions from livestock in Brazil. Beef cattle were identified as the group with the highest total GHG emissions with an annual average of 2, 73E+08 tCO_2eq during the analyzed period. According to Beef Report (2020), beef cattle breeding represents 85% of Brazil's ruminant cattle.

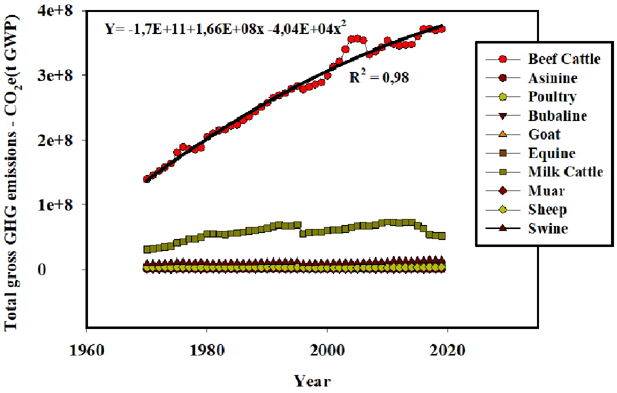
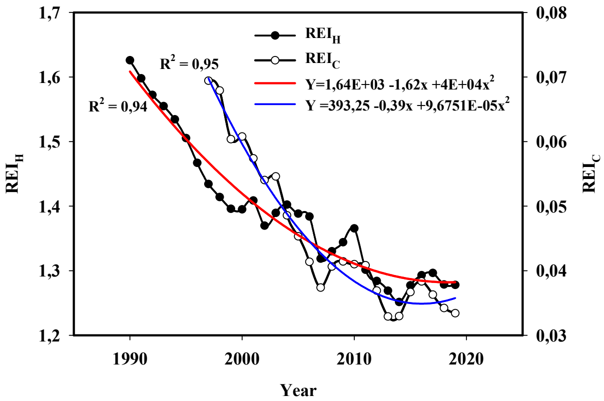


Fig. 1. Total gross CO_2e (t GWP) emission in the period from 1970 to 2019

The enteric CH_4 emissions resulting from ruminants' natural and intrinsic process are 75% of CH_4 emissions in the Agricultural subsectors (MCTI, 2014). Total GHG emissions comprise the sum of emissions from enteric fermentation processes, animal manure management and agricultural soils. Enteric fermentation has the largest share in the total GHG emissions, followed by agricultural soils and animal manure management, with 85,76%, 12,12% and 2,12%, respectively (Table 4). The results in Table 4 presented a low standard deviation in the share of emission processes during the time, indicating that emissions' structure tends to remain relatively constant. It should be noted that livestock contributes to methane emissions in two ways: enteric fermentation and animal manure. Enteric fermentation produces methane during the digestion of food ingested by animals through an anaerobic process carried out by the rumen's bacterial population. In the digestion process, part of the food's carbon is transformed into CO_2 (Duthie *et al*., 2017). The authors report that certain factors can affect the levels of enteric CH_4 production in ruminants, including the type of carbohydrates fermented in the digestive system and the quantity and quality of the food consumed by the animal. The production of methane from animal manure occurs mainly when the manure is handled in liquid form under anaerobic conditions (Shibata and Terada, 2010). Agricultural soils also contribute to GHGs emissions through waste from framing activities, including synthetic fertilizers, animal manure, animal waste deposited on pastures and agricultural crop remains. However, several alternative alternatives were studied and applied to mitigate this risk (Figueiredo *et al*., 2017; Sá *et al*., 2017).

In order to minimize these impacts, the development of more balanced diets and the adoption of management practices that minimizes the relative CH_4 emissions (kg CH_4/kg of meat) in ruminant production systems stands out, providing greater environmental efficiency by reducing the negative impact of animal production for global warming (Ferraz and Felício, 2010; Shibata and Terada, 2010; Duthie *et al*., 2017). Our findings show that the calculated indices have become increasingly better, reflecting the gains in environmental efficiency in the livestock over time. In addition to nutrition, other factors may be contributing to this change and we will discuss them in the following sections.

Reducing negative environmental impact: As one of the largest beef producers, Brazil has an important share in total GHG emissions globally. The results referring to beef cattle from 1990 to 2019 show an increase of 46,8% of the herd (Figure 2). In the same period, there was an increase of approximately 14,8% in net GHG emissions; however, there was a reduction in the HREI and CREI indices (Figure 2). The drops in the indices over the years show that even though there has been an increase in total GHG emissions, efficiency gains in the relationships between GHG emissions and cattle herd and GHG emissions and carcass production could be detected.



Note: HREI =Net GHG emissions (tCO_2eq) divided by the effective herd of beef cattle. CREI = Net GHG emissions (tCO2eq) divided by the carcass weight (kilogram).

Fig. 2. The HREI and CREI indices performance in the beef cattle, Brazil, 1990-2019

Several factors may have contributed to the improvement of these indicators. Among them are the new sustainable production strategies with intensive land use. An example is the integrated agricultural systems where agriculture, livestock and forestry activities are carried out simultaneously in the same area, benefiting from the synergistic effects of system components' interactions (Cardoso *et al*., 2020; Souza Jr. *et al*., 2020). Ferraze Felicio (2010) emphasize that Brazil can reduce enteric CH_4 emissions by i) improving zootechnical production and reproduction rates, like reducing the age of slaughter, reducing the interval between births, reducing the age at first calf; ii) reducing the need for spare matrices and increasing the reproductive longevity of cows; iii) improving the genetic patterns of animals and fodder plants; iv) using food additives and supplements; v) improving feed conversion; vi) improving the handling of both animals and pastures; vi) using good quality water, guaranteeing healthy animals, as sick animals emit more GHG and have their development compromised; and vii) improving animal welfare, releasing animals from stress. Specific strategies can also be considered for nutritional management and ruminal manipulation as alternatives for the relief of H_2 produced by enteric fermentation and reducing the population of methanogenic microorganisms (Shibata and Terada, 2010; Lobato *et al*., 2014). More than 94% of the cattle are raised for meat production and 85.9% of these animals are produced on pasture. This is a favorable characteristic that may contribute to reducing total GHG emissions per kg of the carcass (Cottle and Kahn, 2014; Beef Report, 2020). Table 5 shows the correlation matrix for the variables used in the present study. The results show a positive correlation between the herd and the net GEE emissions, indicating that the increase in the number of animals led to increased net GHG emissions. However, the HREI presented a negative correlation with net GHG emissions and the cattle herd. It is inferred that, even with an increase in cattle herd and net GHG emissions, there was greater efficiency in Brazilian livestock production since the relative GHG emissions per unit weight of carcass and per number of animals in the herd decreased over the years. It is noteworthy that the increase in the herd has been accompanied by an increase in the total GHG emissions, especially when the emitting processes become practically constant. However, even with the increase in total GHG emissions, it must be considered that there was also a fraction of carbon sequestered during the production processes. The level of carbon sequestration will depend, in part, on the profile of the beef cattle production system. In this sense, Souza Jr. *et al*. (2020) report that the pattern of beef cattle production in Brazil has changed with the introduction of new technologies and the intensification of land use in a sustainable manner.

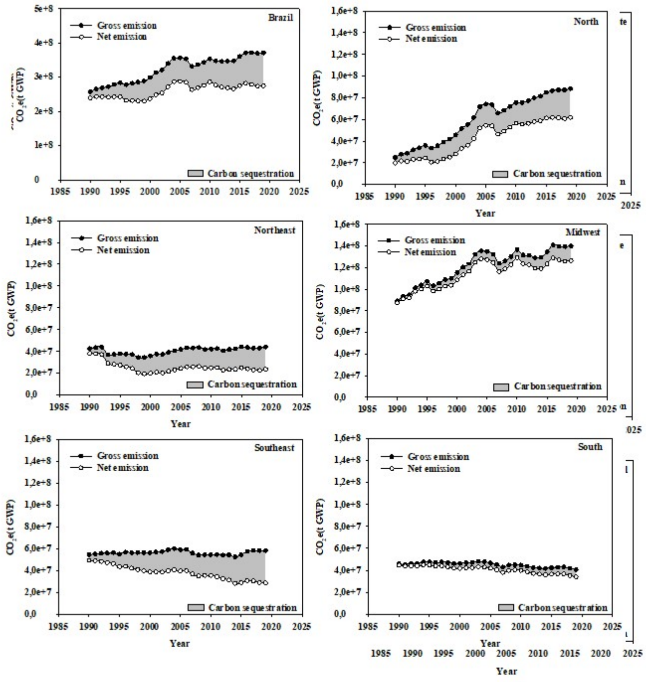


Fig 3. Gross and net GHG emissions, and carbon sequestration of beef cattle production, Brazil, 1990-2019

Figure 3 shows gross and net GHG emissions and carbon sequestration of beef cattle production for Brazil and regions. The gap in the area between the gross and net GHG emissions' lines has gradually widened, showing that the carbon sequestration by beef cattle production has grown over time. Gross GHG emissions show a more pronounced growth trend in the North and Midwest regions, where the herd has also grown more intensively, and the total emissions are higher. The Northeast and Southeast regions tend to stabilize gross GHG emissions, while in the South region, gross emissions have been decreasing since the 2000s. The gains in net GHG emissions observed in Brazil have been strongly influenced by the North, Northeast and Southeast regions' performance. In this regard, the Southeast region has a marked downward trend in net GHG emissions over time. The rate of carbon sequestration by Brazilian beef cattle systems grew from 7% in 1999 to 26% in 2019.

The findings suggest that beef cattle production systems have improved their efficiency measured by the relation between net GHG emissions and total GHG emissions in all regions. Efficiency gains can occur by improving zootechnical indices and pasture management. When the effect of expansion in land use and animals' performance were analyzed to explain the growth in Brazilian beef cattle production, the conclusion was that zootechnical performance explains most (Lampert *et al*., 2020; Carvalho *et al*., 2021; Cezimbra *et al*., 2021). In other words, Brazilian beef cattle production has improved its efficiency, mainly in its animal dimension (Souza Jr. *et al*., 2020; Cezimbra *et al*., 2021; Jaurena *et al*., 2021). However, such a conclusion cannot be generalized for all farms. Lobato *et al*. (2014) stated that there are extremes, ranging from simple farms with low technology and extensive pasture production to intensive systems with forage, strategic feed supplementation, updated health programs and genetic improvement. The authors also mention the emergence of a new generation of professionals with multidisciplinary training and a holistic view of management practices for the entire production chain to reduce greenhouse gas emissions in the production of pasture-fed beef cattle.

The importance of zoning assessment: The future challenge for livestock systems will be maximizing meat production while reducing net GHG emissions. From the perspective of climate change, livestock systems can be beneficial or harmful to the environment, depending on the balance between total GHG emissions and carbon sequestration. As our findings suggest, national, regional, and local monitoring of GHG emissions and carbon sequestration is essential to monitor production systems' efficiency. Brazil's wide territorial dimension and the differences in livestock systems between regions can make national indices less useful for the management of environmental policies. To assess the degree of heterogeneity across the national territory, the efficiency indices were calculated by its regional units (Table 6). From the value of the indices, clusters of states were created by statistically homogenous values. The results indicate that the Midwest region has the largest herd, followed by the North, Southeast, South, and Northeast regions. Consequently, the Midwest region also has the highest net GHG emissions, followed by the other regions according to the herd size. The highest value for the HREI index is also in the Midwest region, showing a higher level of emissions per animal when compared to the other regions. The Northeast region has the lowest GHG emissions per animal, while the Northeast and South regions presented the highest GHG emissions per kilogram of carcass produced. When the states belonging to the same region did not significantly differ, the regional indices can be considered. Therefore, the results indicate that stakeholders can use the regional indices as parameters to define their productive and public policy actions. Thus, states can be classified by the indices average, representing the regional average illustrated in Figure 4. When comparing the regions, it was observed that the North region presented an increase in GHG emissions per animal. On the other hand, the North region showed the highest efficiency, reducing the GHG emissions per kilogram of carcass produced. Besides, it can be said that all regions decreased the GHG emissions per unit of the carcass during the time evaluated.

The increase in the HREI index in the North region is because the net emission increased more than the number of the herd (IBGE, 2019). While net emissions increased by 191.44%, the herd increased by 157.08%, resulting in an increase of 13.37% in the HREI index. In other words, the positive variation occurred because net issuance increased in a greater proportion than the effective beef cattle herd. The efficiency of livestock production systems has been improved over the years, being demonstrated by the negative variation in HREI and CREI values. This means reducing net GHG emissions per animal (-10.90%) and per kilogram of meat produced (-51.87%). The reduction in emission rates is perceived both in the states and regions, even at different levels. The differences demonstrate opportunities for regionalized actions, especially in regions with a greater relative share of Brazil's total emissions. McManus *et al*. (2016) identified a strong acceleration in cattle production in Brazil's North region in recent years. The authors also observed the migration of beef cattle herd from other regions to the North region. The migratory movement is motivated by many issues, like genetic improvement for adaptation of breeds, animal well-being, nutrition, logistics, and economics. The beef cattle herd's productivity has been more sustainable since the net GHG emissions per kilogram of carcass produced varied negatively in all Brazilian regions between 1997 and 2019. The North Region presented the largest negative change with -83.94%, reflecting the herd yield's increase in a cleaner way. Genetic breeding technologies and crop-livestock-forest integrated system have created favorable conditions for farmers and assist cycles of livestock production (Ryschawy *et al*., 2012; Sneessens *et al*., 2016). Integrated systems are based on sharing and maximizing the use of resources and the synergism between them, ensuring environmental balance and reducing the commercial risks by diversifying the agricultural activities model (McManus *et al*., 2016; Figueiredo *et al*., 2017). Besides, other factors are reported in the literature, such as improved pasture management, supplemented diets, selection of animals with better feed conversion rates (Carvalho *et al*., 2021; Jaurena *et al*., 2021). In the 1960s, when the federal government realized that Brazil could be a major exporter of beef, some programs with tax incentives and subsidized rural credit were created to encourage and financially support farmers. Since then, an increase in the production of *Bos indicus* and grasses (*Brachiaria*) has been observed throughout the Brazilian territory, mainly in the Midwest and North regions, considered as expansion zones for agriculture and livestock at that time (Ferraz and Felicio, 2010; Martha *et al*., 2012). Until the 1990s, beef cattle farming in Brazil was recognized as low technological investment, low production costs and large areas required to become economically viable.

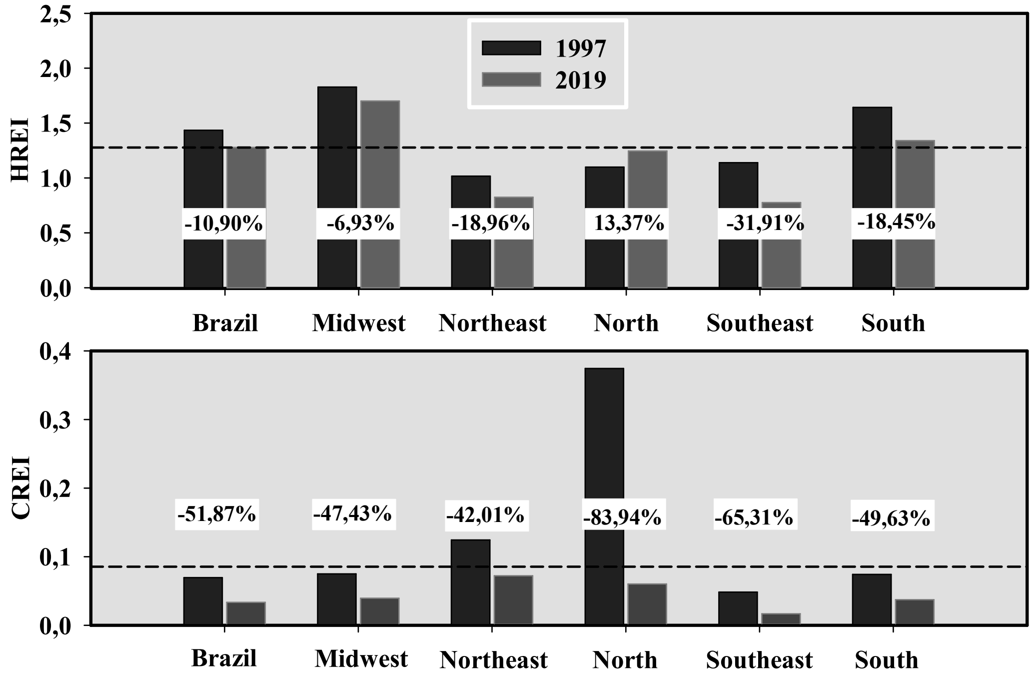


Fig 4. Relative change in HREI and CREI by region, Brazil, 1997-2019

Table 1. Research data: variables, units, period and sources

Variable	Unit	Period	Source
Gross GHG emissions	tCO_2eq	1970-2019	SEEG (2021)*
Net GHG emissions	tCO_2eq	1990-2019	SEEG (2021)*
Effective herd of beef cattle	1,000 of animals	1997-2019	IBGE (2021)
Carcass weight	Kilogram	1997-2019	IBGE (2021)

*Note: The Greenhouse Gas Emissions and Removal Estimation System (SEEG) produces annual estimates of greenhouse gas (GHG) emissions in Brazil. Estimates are generated according to the guidelines of the Intergovernmental Panel on Climate Change (IPCC). The methodology is available in the study by Azevedo et al. (2018).

Table 2. Brazilian geopolitical division: regions and states

Region	States
North	Acre (AC); Amazonas (AM); Rondônia (RO); Roraima (RR); Amapá (AP); Pará (PA); Tocantins (TO);
Midwest	Mato Grosso (MT); Goiás (GO); Distrito Federal (DF); Mato Grosso do Sul (MS);
Southeast	Minas Gerais (MG); Espírito Santo (ES); Rio de Janeiro (RJ); São Paulo (SP);
Northeast	Maranhão (MA); Piauí (PI); Ceará (CE); Rio Grande do Norte (RN); Paraíba (PB); Pernambuco (PE); Alagoas (AL); Sergipe (SE); Bahia (BA);
South	Paraná (PR); Santa Catarina (SC); Rio Grande do Sul (RS);

Table 3. Average and total GHG emissions by animal groups, Brazil, 1970-2019

Animal Species1	n	Total Emissions tCO_2eq	Average Emission (1970-2019)
Asinine	50	2,59E+07	5,18E+05^{c}
Muar	50	3,35E+07	6,69E+05^{c}
Poultry	50	9,01E+07	1,80E+06^{c}
Goat	50	9,58E+07	1,92E+06^{c}
Bubaline	50	9,95E+07	1,99E+06^{c}
Sheep	50	1,57E+08	3,14E+06^{c}
Equine	50	2,19E+08	4,37E+06^{c}
Swine	50	5,41E+08	1,08E+07^{c}
Milk Cattle	50	2,89E+09	5,79E+07^{b}
Beef Cattle	50	1,36E+10	2,73E+08^{a}

Note: Means followed by the same letter in the column do not differ by the Scheffé test at 5% probability

Table 4. Participation of emission processes in total GHG emissions, Brazil, 1970-2019

	Enteric fermentation	Animal waste management	Agricultural soils	Total
Total GHG emissions^{a}	1,17E+10	2,98E+08	1,65E+09	1,36E+10
Share (%)	85,76%	2,12%	12,12%	100%

Note:^{a} Total gross GHG emissions in tCO_2eq.

Table 5. Correlation matrix for the variables: HREI, CREI, net GHG emissions, carcass weight and cattle herd

	HREI^{c}	CREI^{c}	Net GHG emissions	Carcass weight	Cattle Herd
HREI^{c}	1				
CREI^{c}	0,882^{a}	1			
Net GHG emissions	-0,463^{b}	-0,774^{a}	1		
Carcass weight	-0,878^{a}	-0,991^{a}	0,783^{a}	1	
Beef cattle herd	-0,782^{a}	-0,944^{a}	0,914^{a}	0,952^{a}	1

Note:[a] Significant Pearson correlation at the 0,01 level. [b] Significant Pearson correlation at the 0,05 level. [c]HREI is the ratio betweennet GHG emissions and effective beef cattle herd; CREI is the ratio between net GHG emissions and the carcass weight (kilogram).

Table 6. Regional beef cattle herd, total GHG emissions, HREI, CREI and carcass weight, Brazil, 1997-2019

Variables	Midwest	Northeast	North	Southeast	South
Beef cattle herd	6,86E+07^{a}	2,68E+07^{c}	3,83E+07^{b}	3,82E+07^{b}	2,72E+07^{c}
Total GHG emissions^{1}	1,28E+08^{a}	4,07E+07^{d}	6,87E+07^{b}	5,65E+07^{c}	4,46E+07^{d}
HREI^{2}	1,75E+00^{a}	8,68E-01^{d}	1,25E+00^{c}	9,31E-01^{d}	1,45E+00^{b}
CREI^{3}	5,25E-02^{bc}	7,20E-02^{ab}	9,47E-02^{a}	2,71E-02^{c}	5,78E-02^{b}
Carcass weight	2,40E+09^{a}	3,32E+08^{d}	6,57E+08^{c}	1,42E+09^{b}	7,21E+08^{c}

Notes: Means followed by the same letter in the line do not differ by the Scheffé test at 5% probability.[1]Total gross GHG emissions. [2] Net GHG emissions in relation to the effective beef cattle herd. [4] Net GHG emissions in relation to carcass weight (kilogram).

However, beef cattle production changes have intensified since 1994 with the introduction of new technologies such as integrated production systems, genetic improvement, recovery of degraded pastures, and the use of rotated grazing, among others. (Lobato *et al*., 2014; McManus, *et al*., 2016; Godfray, 2015; Jaurena *et al*., 2021). Some factors allowed the increase in productivity, and since the 2000s, the feedlots turned into reality for the beef industry and the number of cattle finished in this system increased. Currently, 14.6% of the slaughtered animals come from the feedlot system (Lobato *et al*., 2014; Ferraz and Felicio, 2010; Beef report, 2020). The adoption of new technologies has brought benefits to beef cattle production systems since farmers can manage costs, profits and risks associated with cattle farming. In this sense, feedlots have been responsible for part of this change, as they play an important role in shortening the production cycle and consequently improving meat quality (Carvalho *et al*., 2021; Jaurena *et al*., 2021). Still, according to the authors, investments to modernize feedlots, the use of *Bos taurus* genetics, and finished animals at a younger age have contributed to GHG mitigation.

In summary, the main technological changes observed in Brazilians beef cattle farming in recent years can be listed from Berndt and Tomkins (2013), Souza Jr. *et al*. (2020) and Carvalho *et al*. (2021) as 1) use of mineral supplements, non-protein nitrogen (urea) for animals in the pasture during the dry season (winter) to increase dry matter intake and prevent loss of body weight; 2) energy and protein diets are supplied to the animals in the pasture throughout the year; 3) pasture management by adjusting stocking rate and soil fertilization for forage production; 4) use of feedlot operations and by-products from agricultural industries, such as citrus pulp, cottonseed, soybean hulls and cane bagasse, to formulate feedlot diets; 5) the use of other breeds, such as Angus and Hereford, to produce crossbred animals based on Nellore breed; and, 6) reducing the land use and deforestation for beef cattle farming. These technologies help reduce emissions through efficiency gains by improving the digestibility of feed and breeding which increases the animal weight in a shorter time. To better evaluate livestock production, avoid distortions, have conclusions that reflect reality and bring development to the sector, it is necessary to observe the dynamics of the carbon cycle in production processes. Besides, it is essential to consider all the elements present in the soil-plant-animal-atmosphere relationship since the interactions result in GHG emitter and carbon sequestration. The carbon sequestered by pastures and crops in integrated production systems mitigates the GHG emitted by animals. Livestock is an activity that generates multiple benefits to society, providing food, nutrients, income, jobs, traction force, basic inputs for clothing and footwear manufacture, among others. Despite this, the image of beef cattle farming has been framed as a polluter activity. A change in how the consumers have seen animal protein production is fundamental to changing this frame (Shibata and Terada, 2010; Lobato *et al*., 2014). Finally, in any human activity, however efficient it may be, there will always be some level of impact on the environment. Therefore, scientific knowledge must be used to search for efficient livestock and management systems, which produce more and are environmentally friendly. One way to do this is by minimizing total GHG emissions while maximizing the carbon removal rates.

CONCLUSION

The results of this analysis showed that the existence of national and regional indexes is differentiated, this must develop to the territorial extension of Brazil, to the climatic variability and to the different production systems, genetic and food factors. For this reason, our study shows that only a national GHG emission index may not be representative for the country. The main results indicate a reduction in the emission of greenhouse gases in the period analyzed throughout Brazil, while an increase in the national cattle herd is observed. An improvement in the performance of the animals was noticed through the increase in the carcass yield (Kg / Head), demonstrating greater efficiency in the productive process in this period. The regional indexes obtained to the proposed objective demonstrate that they can be used as a parameter to verify the efficiency of the evaluation gases. These indices can help as an alternative tool for the definition of national inventories and policy definitions aimed at the productive sector. The methodological reordering used in this research can also be applied to other countries that have large territories, with greater precision in the composition of representative indexes for GHG by zoning.

Limitations of the study: The factors that explain the improvement of GHG emissions and carbon sequestration rates were inferred through the theoretical-scientific basis. For this reason, we suggest carrying out new studies seeking to identify the changes that have occurred in each region related to the insertion of new technologies and changes in the beef cattle production systems in the last 20 years.

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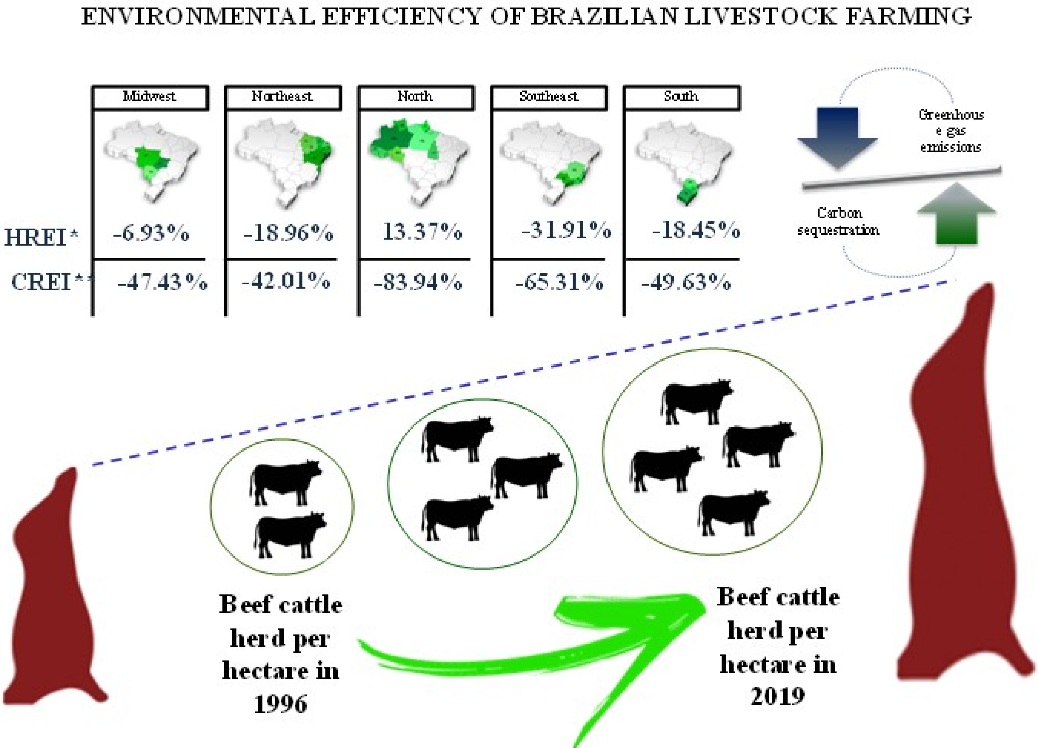

Note: ***HREI:** Herd Relative Emissions Index = Net greenhouse gas emissions (tCO^{2}eq) divided by the effective herd of beef cattle.
****CREI:** Carcass Relative Emissions Index = Net greenhouse gas emissions emissions (tCO^{2}eq) divided by the carcass weight (kilogram).

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