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Brazilian Beef Production and GHG Emission—Social Cost of Carbon and Perspectives for Climate Change Mitigation

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Abstract: Among all Brazilian economic sectors, the livestock sector stands out due to its large production and high export volume. However, beef production is associated to significant environmental impacts, such as deforestation and greenhouse gas (GHG) emission. The Paris Agreement was settled to avoid that global mean temperature rise up to 1.5 – 2º C by 2100. In 2020, Brazil committed in its nationally determined contribution (NDC) to reduce its GHG emission by 43% until 2030. This study aims to identify the association of beef production and beef cattle emissions, as well as assess predictive GHG emission scenarios for 2030 and value these emissions. To translate the environmental impacts of beef production into economic impacts, and thus amplify the discussion, we valued GHG emissions using the social cost of carbon (SCC). The results showed that the business as usual (BAU) GHG emission derived from beef production would range between 0.423 and 0.634 $GtCO_2e$ in 2030, whereas the maximum emission estimated to meet the NDC should be 0.257 $GtCO_2e$. The SCC revealed the opportunity to reduce between US $18.8 and $42.6 billion in the cost of BAU emissions from beef production in 2030 if the NDC is met. Lastly, assessing a scenario where climate targets and beef exports are prioritized, between 2-10 kg of beef per capita would be available in the domestic market in 2030. Our results reveal the need and urgency of changes in livestock production to emit less GHG per kg of beef produced, and the avoided monetary cost of reducing emissions.

Keywords: greenhouse gas; Paris Agreement; social cost of carbon; livestock; beef

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1. Introduction

Livestock is a relevant activity in the Brazilian socio-economic scenario, as the country is the world's largest exporter, second largest producer and third largest consumer of beef (ABIEC, 2022; Belik, 2020; Ritchie et al., 2017). However, livestock production is also associated with significant environmental impacts, such as deforestation and high greenhouse gas (GHG) emission rates (Ribeiro et al., 2018; Roubuste et al., 2022).

In 2021, Brazil ranked fifth in global GHG emissions (Ritchie et al., 2020). In the same year, beef cattle accounted for 65% of total emissions from the Brazilian agricultural sector as well as 16% of Brazilian total emissions (SEEG, 2023). The direct sources of GHG emission in the agricultural sector include enteric fermentation and management of agricultural soils and manure (Cerri et al., 2009; SEEG, 2021). The type of livestock production system has an influence on GHG emissions rates, and changes in agricultural production systems can be important strategies to mitigate global warming (Bogaerts et al., 2017; de Oliveira Silva et al., 2015; Eri et al., 2020; Gil et al., 2018). The Brazilian Plan for Adaptation and Low Carbon Emission in Agriculture 2020-2030 (ABC+ Plan) integrates strategies and targets to reduce GHG emissions from agricultural production, as well as to increase its efficiency and resilience against climate change (Brasil, 2021a).

The Paris Agreement was established in 2015 at the 21st Conference of the Parties (COP21) with the main objective of limiting the increase in global mean temperature to between 2 and 1.5ºC above pre-industrial levels. In 2020, Brazil has established its Nationally Determined Contributions (NDC)

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(Brazil, 2020), committing to reduce GHG emissions by 43% until 2030, considering the 2005 emissions as a baseline, which corresponds to a maximum emission of 1.6 GtCO_2e.

Beef cattle's environmental impacts, namely environmental externalities, can be translated into financial costs through environmental economic valuation (Motta, 1997). The social cost of carbon (SCC) is the monetary value assigned to the future damage caused by each additional ton of CO_2e emitted (Carreira, 2015; Rennert et al., 2022; Stern, 2006; UNEP, 2014). The damages considered include impacts of global warming and extreme weather events on agricultural production, population health and safety, and loss of biodiversity and ecosystem services (Beach et al., 2016; Kauffman et al., 2022). Despite the several studies applying the SCC concept in a variety of production sectors and contexts (Beach et al., 2016; Briggs et al., 2016; Rode et al., 2021), to date, no studies have been found in the literature applying SCC in the Brazilian livestock sector.

Considering the given context, this study aims to evaluate the association between beef production and beef cattle emissions in Brazil, to value the GHG emissions and elaborate predictive scenarios of GHG emissions for 2030, aiming to identify the feasibility of meeting the targets established in the NDC.

2. Methods

The methods used in the present article comprise temporal descriptive analyses, statistical tests, qualitative and quantitative exploratory approaches in order to establish the predictive scenarios, and environmental economic valuation. For the statistical analyses and production of graphs and tables, we used JASP version 0.14.1, R-software version 4.0.2, IBM SPSS version 26.0, and Microsoft Excel.

2.1. Data of the Study Variables

GHG emission. Brazilian data on total GHG emissions (tCO_2e) and by sectors – waste, industrial process, energy, land use change (LUC), and agriculture – were collected, for the period 2000 to 2020, from the Brazilian data platform System for Estimating Greenhouse Gas Emissions (SEEG) (SEEG, 2023). The SEEG data and estimates are derived from government reports and prepared according to the guidelines of the Intergovernmental Panel on Climate Change (IPCC) and the methodology of the Brazilian Inventories of Anthropogenic Greenhouse Gas Emissions and Removals, elaborated by the Ministry of Science, Technology, and Innovation (de Azevedo et al., 2018).

Beef production. Data on Brazilian beef production, for the period 2000 to 2020, were obtained from the Quarterly Animal Slaughter Survey prepared by the Brazilian Institute of Geography and Statistics (IBGE) (IBGE, 2023). The data is retrieved from slaughterhouses under federal, state or municipal health supervision.

Beef production and export projections. BAU projection data on beef production for the period 2021 to 2030 were obtained from the Agricultural Business Projections Report – Brazil 2020/21 to 2030/31, and is estimated at 9.6 million tons (t) (Brasil, 2021b). The beef export projection for 2030 was obtained from the same report, and is estimated at 3.5 million t (Brasil, 2021b). The projection was prepared by the Ministry of Agriculture, Livestock and Food Supply (MAPA) and the Brazilian Agricultural Research Corporation (EMBRAPA) in partnership with the Department of Statistics of the University of Brasilia based on data from the National Supply Company (CONAB).

CO_2e/t indicator. The ratio between GHG emissions (CO_2e) and beef production (t), i.e., how many tons of CO_2e are emitted to produce one ton of beef (tCO_2e/t), was calculated by the authors based on data from SEEG (2023) and IBGE (2023) and using the following equation:

$$Indicator\ (tCO2e/t) = \frac{Beef\ cattle\ emission\ (tCO2e)}{Beef\ production(t)} = \frac{378.394.274\ (tCO2e)}{7.824.888\ (t)} = 51{,}86\ (tCO2e/t) \quad (1)$$

The data on GHG emissions from beef cattle (SEEG, 2023) and beef production (IBGE, 2023) are an average of the 21 years analyzed (2000 to 2020).

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However, the emissions data used for beef cattle do not account for indirect emissions associated with beef production, such as deforestation, machinery use, and soil liming. Seeking a more precise analysis, we prospected the literature for previously published indicators that include indirect emissions from beef cattle production, and selected two indicators to compose the analysis.

Social Cost of Carbon (SCC). The SCC value was obtained from a study conducted by the United Nations Environment Programme (UNEP, 2014). Using the Stern Report (2006) as a reference, UNEP (2014) has updated the SCC for the year 2012 in a BAU scenario and estimates it to be US $113. The GHG emission value estimated for 2030 based on the predictive scenarios will be calculated using the following equation:

$$SCC\ in\ 2030\ (biUS\$) = Emission\ estimatives\ (GtCO2e) \times SCC\ (\frac{US\$}{tonCO2e}) \tag{2}$$

The Stern Report (2006) is a widely used and discussed reference in SCC valuation studies (Briggs et al., 2016; Dennig et al., 2015; Hope et al., 2006; Rode et al., 2021; van den Bergh and Botzen, 2015). The statistical analysis model used by the authors of the Stern Report is the PAGE (Policy Analysis of the Greenhouse Effect), which encompasses in its variables the effects of the increase in global mean temperature, as well as the costs of implementing preventive public policies (IPEA, 2022; Stern, 2006). The international recognition of the Stern Report and the compatibility of the PAGE model with the scope of the present study justify the choice of a more updated SCC to compose the analyses (UNEP, 2014). It is important to note that the SCC value used is a global average, which is justified by the fact that local GHG emissions become a global problem due to climate change.

2.2. Statistical Analysis

For the descriptive analysis, we calculated the mean, minimum and maximum value, standard deviation and error of the beef production data, total CO_2e emissions and emissions by sectors, as follows: i) waste; ii) industrial process; iii) energy; iv) land use change; v) agriculture; vi) beef cattle. Linear regression analysis was applied in order to investigate the functional relationship between the independent variable (beef production) and the dependent variable (beef cattle emission).

2.3. Predictive Scenarios for 2030

Based on the aforementioned indicators, it was possible to develop the following predictive scenarios:

Scenario of BAU GHG emissions from beef cattle forecasted for 2030. Estimate of how much will be emitted by beef production in 2030 based on the selected indicators and the beef production projection for 2030 (Brasil, 2021b).

Scenario of maximum GHG emissions from beef cattle to meet the NDC. To estimate the maximum beef production required to meet the NDC, it is first necessary to estimate its maximum GHG emission within the total Brazilian limit of 1.6 $GtCO_2e$, as stipulated in the NDC. The present study proposed to calculate the temporal mean (2000-2020) and standard deviation of the GHG emissions data of each sector – waste, industrial process, energy, agriculture, land use change – and the subsector beef cattle, as well as each sector's respective percentage on total GHG emissions. From these results, it was possible to calculate beef cattle's emission considering a total Brazilian emission of 1.6 $GtCO_2e$, that is, the maximum emission from beef cattle to achieve the NDC in 2030.

Scenario of maximum beef production to meet the NDC. Given the maximum GHG emission value of beef cattle for 2030, the maximum value of beef production to meet the NDC targets was calculated using the selected indicators and Equation 1.

Estimate of impacts on Brazilian domestic market. Brazil's total beef production is divided into domestic market and exports (Equation 3).

$$Total\ Brazilian\ production = domestic\ market + exports \tag{3}$$

To the amount available on the domestic market, is added Brazil's imports. Beef imports, however, were not considered in our analyses since the scope of the study aim to assess only the

Brazilian beef production. Furthermore, imports compose a small percentage of the beef available for the domestic market, accounting for only 1.1% in 2020 (CONAB, 2022). Thus, using the beef export projection for 2030 (Brasil, 2021b), we calculated how much beef will be available for consumption on the domestic market.

2.4. Valuation of the Estimated Emissions—Social Cost of Carbon

Lastly, in order to estimate the economic impact of GHG emission derived from Brazilian beef production, we used the SCC method. The valuation was applied on the BAU emission scenario and on the scenario of maximum emission to meet the NDC targets.

3. Results

3.1. Statistical Analysis—GHG Emissions from Beef Production

Beef production and CO_2e emissions from beef cattle increased throughout the analyzed period (Figure 1). From 2000 to 2020, beef production doubled while the emissions increased by 27%. It is noticeable that at the beginning of the period of analysis, specifically between 2000 and 2006, both curves are further apart in comparison to the following years (2007 to 2020).

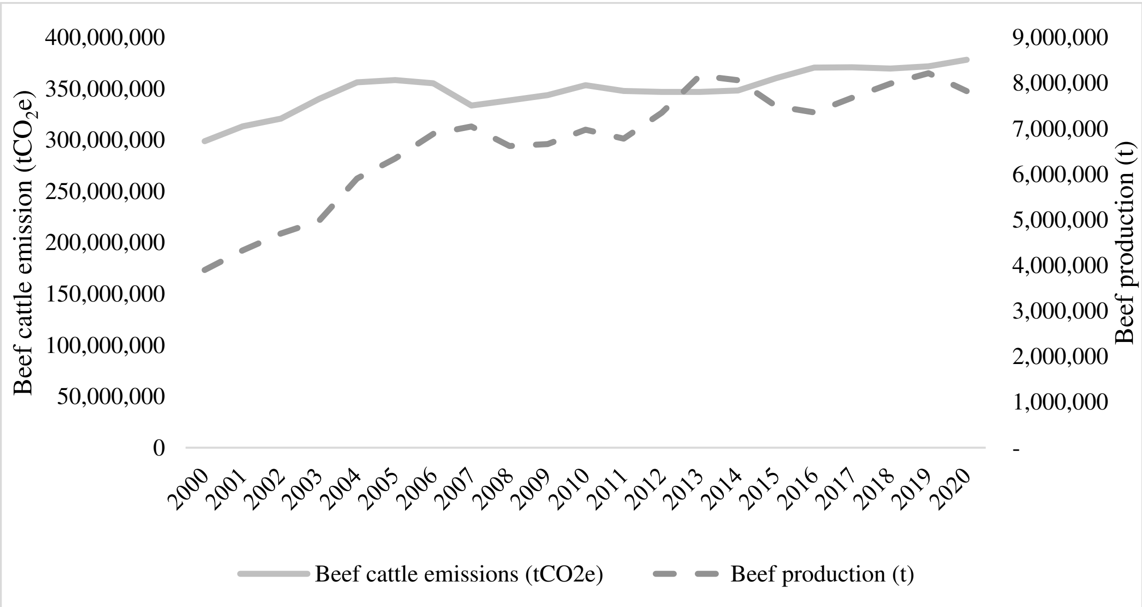

Figure 1. Beef production (t) and beef cattle emission (tCO_2e) from 2000 to 2020.

The descriptive analysis for the period indicated that the average annual beef production was 6.728 million t, and emissions from beef cattle, in $GtCO_2e$, were 0.3489 million (Table 1). Production and emissions values peaked in 2019 and 2020, respectively.

Table 1. Descriptive analysis of beef production and beef cattle emission data.

	Beef Production (million t)	Beef Cattle Emission ($GtCO_2e$)
Mean	6.728	0.3489
Standard Deviation	1.287	0.02016
Error	280770.062	0.004399
Minimum (year)	3.900 (2000)	0.2989 (2000)
Maximum (year)	8.219 (2019)	0.3784 (2020)

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The linear regression resulted in a coefficient (R^2) of 0.654 (Table 2), validating the functional relationship between beef production (independent variable) and beef cattle emission (dependent variable).

Table 2. Linear regression coefficients of the beef production (t) and beef cattle emissions (tCO_2e) variables between 2000 and 2020.

Dependent Variable: Beef Cattle Emission tCO_2e							
Equation	**Model Summary**					**Parameter estimate**	
	R^2	**F**	**df1**	**df2**	**Sig.**	**Constant**	**b1**
Linear	.654	35.943	1	19	.000	263617346.837	12.673

Based on the angular (b1 = 12.673) and linear coefficients (Constant = 263617346.837), it was possible to obtain the equation (Equation 4) that defines the line of the analyzed variables (Figure 2).

$$y = 12.673x + 263617346.837 \quad (4)$$

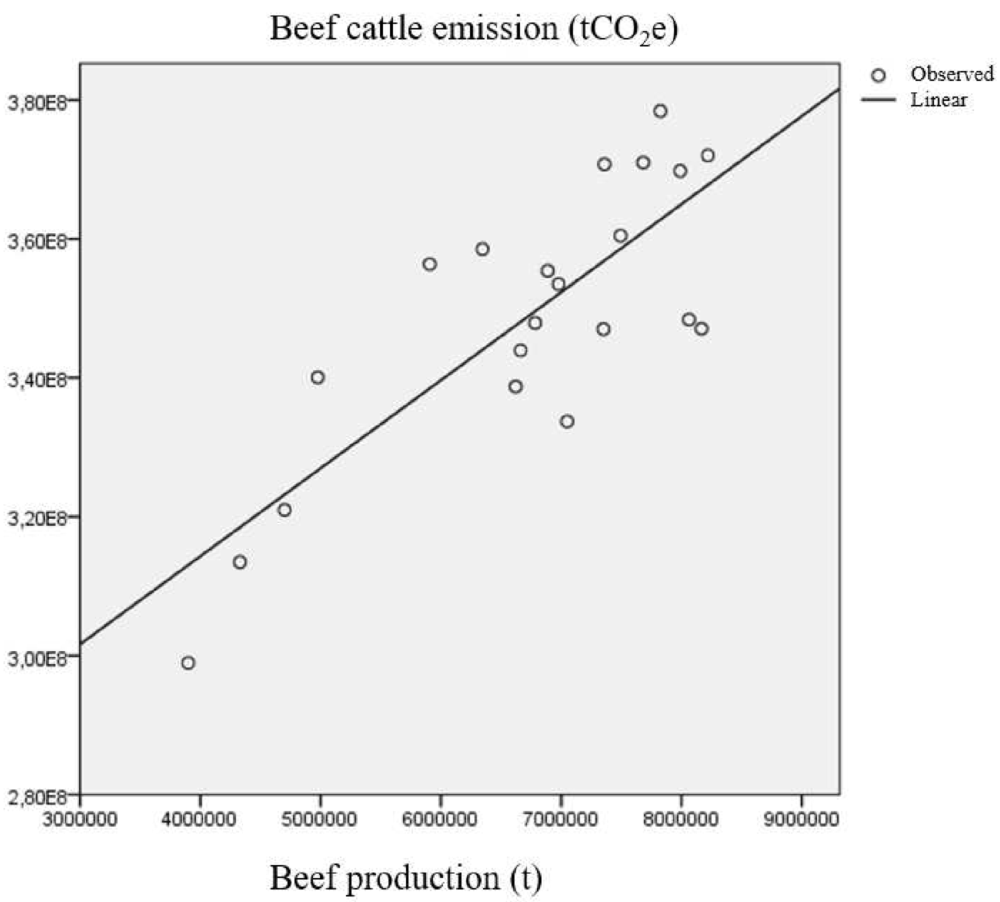

Figure 2. Graph of the relationship between the variables beef production (t) and beef cattle emissions (tCO_2e) for the analyzed period (2000 to 2020).

3.2. Indicators of GHG Emission Per Ton of Beef Produced (tCO_2e/t)

The amount of CO_2e emitted from beef production varies according to the production system. In general, the extensive system has higher emission rates compared to the intensive system because the latter incorporates a range of pasture management and land use techniques, as well as cattle feeding strategies, to reduce GHG emission rates. In addition, there is a range of methodologies and variables that can be used to assess the emission rate from livestock production, and this varies

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between studies. This explains the wide range of indicators prospected in the literature, which are showed on Table 3 along with the main variables used on each study.

Table 3. Values and mains variables considered on the indicators (tCO_2e/t and $kgCO_2e/kg$ beef protein) prospected on previously studies and the indicator calculated by the authors.

	tCO_2e/t							$kgCO_2e/kg$ Beef Protein
	11.5[1]	**19.9**[2]	**28**[3]	**44**[4]	**52**[5]	**58**[6]	**66**[7]	**295**[8]
Brazil	X		X	X	X	X	X	
Worldwide		X						X
Intensive system	X							
Intensive and extensive system		X	X	X	X	X	X	
Emissions from production	X		X	X	X			
+ emissions from LUC				X			X	
+ emissions from transport and beef cooking						X		

Data source: Imaflora, 2022[1]; Vasconcelos and Zaparolli, 2022[2]; Cederberg et al., 2009[3]; Cederberg et al., 2011[4]; calculated by the authors based on data from SEEG, 2023 and IBGE, 2023[5]; Saget et al., 2021[6]; Persson et al., 2014[7]; FAO, 2015[8].

Considering the wide range of prospected values, the selection of the indicators for the analyses was based on compatibility with the scope of the study. Exclusion criteria included study location and year, as well as production system and production stages evaluated. Therefore, we excluded the worldwide indicators (FAO, 2015; Vasconcelos and Zaparolli, 2022), the indicator that did not included both intensive and extensive production system (Imaflora, 2022), the indicator that extrapolated beyond the farm-gate production (Saget et al., 2021), and the outdated indicator (Cederberg et al., 2009) (Table 3). Seeking a well-grounded range of estimates to complement with the indicator calculated using secondary data (namely indicator B), it was selected an indicator that considered both direct and indirect emissions from Brazilian beef production (Cederberg et al., 2011), namely indicator A, and an indicator that considered only indirect emissions (Persson et al., 2014), namely indicator C (Table 4).

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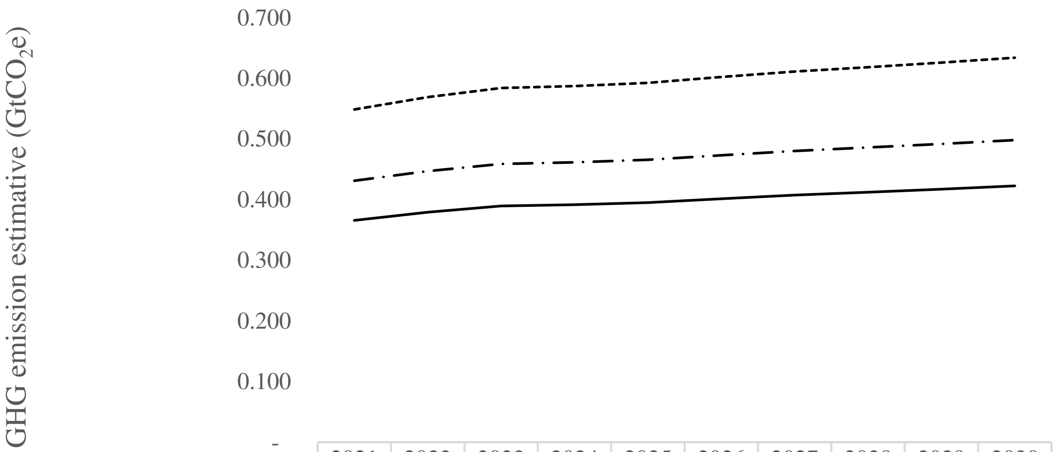
Table 4. Indicators used on the analysis.

	Indicators
A	44 tCO_2e/t
B	52 tCO_2e/t
C	66 tCO_2e/t

Data source: Cederberg et al., 2011 (A); calculated by the authors based on data from SEEG, 2023 and IBGE, 2023 (B), and Persson et al., 2014 (C).

3.3. Scenario of BAU GHG Emissions from Beef Cattle Forecasted for 2030

At the deadline year stipulated in the Paris Agreement, the CO_2e emissions from beef cattle production are estimated to be between 0.423 and 0.634 $GtCO_2e$. Compared to the GHG emissions of 0.378 $GtCO_2e$ in 2020 (Figure 1), beef cattle emissions forecast for 2030 are between 12% and 68% higher (Figure 3).



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Estimate A (GtCO2e)	0.366	0.379	0.389	0.392	0.395	0.401	0.407	0.412	0.417	0.423
Estimate B (GtCO2e)	0.431	0.447	0.459	0.462	0.466	0.473	0.480	0.486	0.492	0.498
Estimate C (GtCO2e)	0.549	0.569	0.584	0.587	0.593	0.602	0.611	0.618	0.626	0.634

Figure 3. Estimates of CO_2e emission from beef cattle calculated from the projection of beef production and the selected indicators.

3.4. Scenarios of Maximum GHG Emissions and Maximum Beef Production to Meet the NDC

Relative emissions results showed that beef cattle accounted for 16% of total Brazilian emissions during the analyzed period (2000-2020) (Table 5). Although beef cattle are a subsector within the agriculture sector, we explored it as an individual sector.

Table 5. Mean and standard deviation of GHG emissions from Brazilian economic sectors, and maximum emissions values for 2030 calculated based on the estimated relative percentage.

Economic Sectors	Mean* [Standard Deviation] ($GtCO_2e$)	Relative Emissions (%)	Maximum Emission Estimate - 2030 ($GtCO_2e$)
Waste	0.072 [0.013]	3.30	0.053
Industrial Process	0.090 [0.011]	4.12	0.066
Energy	0.371 [0.061]	17.04	0.273

Agriculture	0.525 [0.037]	24.11	0.386
LUC	1.118 [0.465]	51.40	0.823
Total	**2.175 [0.383]**	**100**	**1.6**
Beef cattle	0.349 [0.020]	16.04	0.257

*Mean calculated for the period 2000-2020.

Given this percentage, beef cattle emission should be at a maximum of 0.257 $GtCO_2e$ in 2030 to meet the NDC targets (Table 6). Accordingly, the maximum production estimates to meet the NDC vary between 5.8 and 3.9 million tons (Table 6).

Table 6. Maximum beef production estimate for 2030 to meet the NDC targets.

Scenarios	Indicator (tCO_2e/t)	Maximum Emission Estimate for 2030 ($GtCO_2e$)	Maximum Beef Production Estimate (t)
A	44		5,833,419
B	52	0.257	4,955,649
C	66		3,888,946

However, an analysis of the beef production data between 2000 and 2020 (Figure 4) shows that Brazil's annual beef production has not been below 6 million tons since 2004, when it was 5.9 million tons.

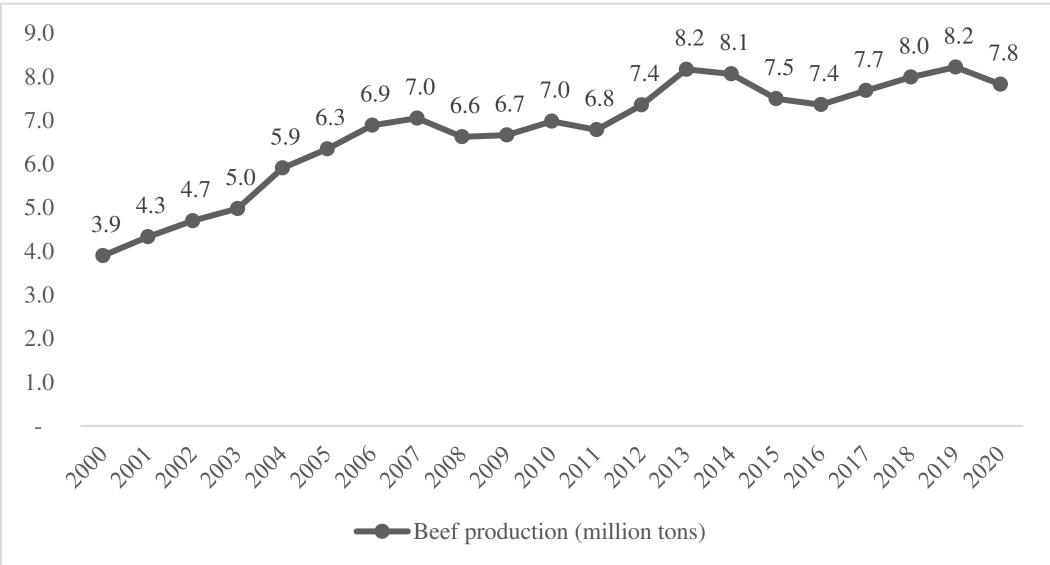


Figure 4. Annual beef production (million tons) between 2000 e 2020. Data source: IBGE, 2023.

Beef production projection (Brasil, 2021b) forecasts a production of 9.6 million tons in 2030, while our estimate shows that beef production should be 2.5 to 1.6 lower to meet the NDC emissions target.

3.5. Estimate of Impacts on Brazilian Domestic Market

Under the assumption of export priority, we estimate that from 2.3 to 0.4 million tons of beef would be available on the domestic market in Brazil (Table 7). Data for 2021 show that 7.24 million ton of beef was available in the Brazilian domestic market (ABIEC, 2022), indicating that the beef availability estimated for 2030 will be far below. Lastly, it was possible to calculate the annual per

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capita availability of beef for 2030 by considering the Brazilian population estimate of 224,868,462 (IBGE, 2022) (Table 7).

Table 7. Estimates of the total and per capita availability of beef for Brazilian domestic consumption in 2030.

Estimates	Maximum Beef Production Estimate (t)	Beef Export Projection (t) for 2030[1]	Beef (t) Available for the Domestic Market in 2030	Beef (t) Available Per Capita (kg/inhabitant/year)
A	5,833,419		2,338,419	10
B	4,955,649	3,495,000	1,460,649	6
C	3,888,946		393,946	2

[1]Brasil, 2021b.

3.6. Valuation of the estimated emissions—Social Cost of Carbon

From the BAU emission estimates, we predict a SCC between US $47.8 and $71.6 billion, and from the maximum emission estimate, we predict US $29.04 billion of SCC (Table 8). These results indicate a potential abatement of US $18.8 to $42.6 billion in GHG emissions costs if beef cattle emissions were limited to the maximum estimated range to meet the NDC.

Table 8. Social Cost of Carbon estimates for 2030 in US$ billion.

Emission Estimates ($GtCO_2e$)		SCC (US$)	SCC Estimated for 2030 (bi US$)
A (BAU)	0.423		47.80
B (BAU)	0.498		56.27
C (BAU)	0.634	113	71.64
Maximum to meet the NDC	0.257		29.04

The ABC+ Program 2020-2030 (Brasil, 2021a) provided, between July/2022 and March/2023, BRL $21 billion in credit to agricultural producers (BNDES, 2023). At the Brazilian Central Bank's average (mean value of the 6 months prior to July/2023) conversion rate of USD = 5.04 Real/BRL, this amount is equivalent to US $4.2 billion (BCB, 2023). Of this total, BRL $9.6 billion (US $1.9 billion) was destined for the purchase of machinery such as tractors and harvesters, and only BRL $608 million (US $121 million) was destined for programs that aim to reduce the environmental impact of agriculture and cattle ranching (BNDES, 2023; BCB, 2023).

4. Discussion

Beef production doubled between 2000 and 2020, while emissions from beef cattle increased by 27% (Figure 1), indicating an increase in beef production efficiency, i.e., more beef could be produced without a proportional increase in GHG emissions from beef cattle. The adoption of intensive practices, such as rotational grazing, feed supplementation and cattle health monitoring, can increase cattle stocking rates, spare land and reduce slaughter age, all of which are effective ways to increase beef production and reduce GHG emissions (Barbosa et al., 2015; Berchielli et al., 2012; de Oliveira Silva et al., 2015; EMBRAPA, 2017; Fonseca de Souza et al., 2022; Gil et al., 2018; Nascimento et al., 2020; Sakamoto et al., 2020). Feed supplementation increases the daily live weight gain, shortening the fattening phase and the slaughter age, thus potentially reducing GHG emission per kg of beef (Florindo et al., 2017; Jose Neto et al., 2018; Marques et al., 2022; Simioni et al., 2022). Rotational grazing, as opposed to continuous grazing, allows pasture recovery and increases the cattle stocking rates, producing more kg of beef per hectare (Sakamoto et al., 2020). Besides guaranteeing the consumer's sanitary security, controlling the herd's health reduces the bovine mortality rate. The findings above mentioned, as well as the indicators prospected (Table 3), show that beef production can generate different GHG emissions rates.

Our results showed that BAU emission is between 1.6 and 2.5 times higher than the maximum emission to meet the NDC. Based on these results, and considering the achievement of the NDC targets as a priority, two solutions can be considered based on two premises. The first solution, assuming no change in the amount of beef produced (i.e., beef production in 2030 will be 9.6 million tons), is to optimize cattle production to reduce the amount of GHG emitted per kg of beef.

Intensive production practices, such as those described above, can be enhanced when combined with pasture restoration and reforestation (Bogaerts et al., 2017; de Oliveira Silva et al., 2015; de Oliveira Silva et al., 2018; Eri et al., 2020; Gil et al., 2018; Valentim and Andrade, 2009). In addition to avoiding emissions from degraded pastures, restoring these areas waives deforestation to open new pastures, and reforestation can help mitigate global warming through carbon sequestration (Cortner et al., 2019; de Almeida et al., 2011; Fernandes and Finco, 2014; IPEA, 2022; Macedo, 2009; Tadini et al., 2022). Furthermore, carbon sequestration can provide carbon credit to farmers (Moreira et al., 2020; Ribeiro et al., 2011).

The second solution, which is now based on a BAU production system premise, is to reduce the amount of beef that is produced and, consequently, the amount consumed. These results indicate that, in this hypothetical scenario, between 2 and 10 kg of beef per capita will be available on the Brazilian domestic market in 2030. On average, Brazilians consumed 27.8 kg of beef in 2021 (CONAB, 2022). Therefore, we observe that in this hypothetical scenario, beef consumption could drop drastically among Brazilians. However, it is important to point out that the average beef consumption value is only a metric tool used to enable the analysis of the proposed scenario, given that the distribution of beef consumption across the country is uneven due to the gastronomic culture of each state (Belik, 2020). Moreover, beef consumption, especially in Brazil, is a delicate and complex issue. Despite the fact that the country is the second largest producer of beef, it is not an affordable food for part of the Brazilian population. Due to the increased price of beef during the COVID-19 pandemic, for example, Brazilians had to resort to other cheaper sources of meat protein, such as chicken, pork, and eggs (Brasil, 2020). Reducing the amount of beef on the domestic market leads to an imbalance between supply and demand, increasing the price of beef and decreasing the purchasing power of the population, thus widening social inequality.

The scenario proposed above does not intend to dictate that beef production must be drastically reduced in order to meet the NDC targets, but it does indicate that beef consumption may be significantly affected if beef production is drastically reduced and exports are prioritized. The proposed scenario also allows us to reflect on the environmental impacts derived from our eating habits. Several studies assess reducing beef consumption as a potential solution to mitigate climate change (Clark et al., 2020; Röös et al., 2018; Sanford et al., 2021; Springmann et al., 2016; Stoll-Kleemann and Schmidt, 2017; Theurl et al., 2020; Weindl et al., 2017).

The elimination of beef consumption is a philosophical lifestyle adopted by several social movements, namely vegetarians and vegans, for its potentially positive reflexes on the environment (Castañé and Antón, 2017; de Oliveira Silva et al., 2021; McAlpine et al., 2009; Saget et al., 2021). However, reducing beef consumption should be an individual choice, not an imposition. The proposed scenario aims to highlight the social impacts of the hypothetical reduction in beef production in order to open the discussion on how to produce enough beef for the domestic market while meeting the targets set out in the NDC.

The SCC revealed how costly GHG emissions from beef cattle production can be, and consequently how environmentally unsustainable cattle production can be. Although these costs are not actually paid for by any country or institution, environmental valuation allows the assessment and debate of current investments in GHG emissions mitigation, as well as guide the formulation of public policies on climate change. The value of SCC should be understood as the costs paid by society due to the negative impacts caused by livestock production, notably environmental pollution (GHG emissions, air pollution and consequently climate change). Addressing climate change should be seen as an urgent need to integrate the social, economic and environmental actions of livestock production (Harrison et al., 2021).

The range of avoided costs estimated by the SCC (US $18.8 to $42.6 billion) indicates how much could be invested presently to reverse the future environmental damage caused by beef production. The US $4.2 billion in credit currently provided by the federal government to farmers to mitigate the environmental impacts of agricultural production is well below the range of potential avoided costs. Approximately half of the credit provided by the federal government in the period July/2022 to March/2023 was for the purchase of tractors and harvesters, while 2.9% was for the incentive program for sustainable farming techniques and integrated production systems, such as integrated crop-livestock-forest systems and pasture restoration (BNDES, 2023). In addition to investing more in intensive practices and integrated systems, the avoided costs could be invested, for example, in monitoring deforestation and encroachment into protected areas, planning for the conservation of ecosystems and biomes, and reforestation (WRI, 2019; IPCC, 2018). It is important to note that in this study we value a portion of the total environmental impact of livestock production. In addition to GHG emissions, land use change for cattle grazing is damaging the biodiversity of Brazilian biomes (Foley et al., 2011; Patiño-Domínguez et al., 2020; Tabeau et al., 2017; Tubiello et al., 2015).

One possible measure to mitigate the impacts of livestock production would be to tax the carbon generated. Cline (2020) proposes compensation for low-income families, as well as partial tax waivers for certified farms and ranches, once low-emission feed and genetic techniques become clearer or widespread animal testing for enteric methane becomes feasible. The use of the tax mechanism is controversial, but it could stimulate investment in more intensive livestock techniques that emit fewer GHGs, resulting in avoided costs of environmental disasters, for example.

Overall, our findings indicate the complexity and diversity of factors involved in meeting climate change targets. The environmental impacts of beef production do not have a single cause, therefore, there is no single solution. Integration between scientific research and farmers can be beneficial for more efficient and low-emission production as researchers seek to identify more up-to-date and environmentally sustainable techniques and technologies. Public policies and credit lines are viable ways to stimulate farmers to implement low-emission production practices. In Brazil, federal ministries can play a crucial role in mediating and integrating research and technology adoption by farmers. The ABC+ Plan fulfills the role of facilitating the investment of livestock producers in intensive practices, but there is low adoption. It is necessary to create other forms of incentives, such as partial tax exemption and carbon credits implementation.

5. Conclusions

The results of this study are primarily intended to reinforce the urgency of reducing GHG emissions in order to mitigate global warming and to provoke reflection on ways to mitigate these emissions in order to minimize the costs of climate change. The estimated GHG emissions in the BAU scenario indicate the unlikelihood of achieving the targets set in the Brazilian NDC, with implications for the objective of limiting the increase in the global average temperature to between 2ºC and 1.5ºC. The SCC estimate emphasizes the environmental and economic infeasibility of the current beef production system, showing the magnitude of the costs that can be avoided and/or invested in intensive livestock production. However, these investments should be made feasible by the federal government through public policy and credit lines. In addition to the environmental impacts, we propose a scenario that highlights the social impacts of high GHG-emitting beef production. Deep changes in the agricultural and livestock system are necessary to ensure sufficient beef production to meet the environmental goals of the NDC, as well as domestic consumption and export demand.

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