Socioeconomic and environmental impacts of degraded pasture recovery in Brazil: contribution to the NDC

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Abstract

Climate change adaptation policies and actions are being promoted by global commitments such as the Paris Agreement. Among the practices for low-carbon agriculture, the degraded pasture recovery (recuperação de pastagens degradadas - RPD) aims to mitigate the greenhouse gases (GHG) emissions caused by cattle, the main source of emissions from the agricultural sector. RPD has shown the capacity to increase cattle production while allowing soil organic carbon (SOC) fixation, however, SOC change is not yet officially considered by Brazil. This paper evaluates the impacts of degraded pastures recovery in Brazil on socioeconomic aspects and on GHG mitigation targets of the Nationally Determined Contribution (NDC). We used a Computable General Equilibrium model, TERM-BR15, simulating three scenarios for the period 2015 to 2035. Scenario 1 (SC1) simulates RPD shocks of livestock productivity, investments, and SOC fixation. Scenarios 2 and 3 are sensitivity analyses. For the impacts on emissions two carbon accounting methods were considered, the original method of Brazil's emissions inventory, which does not take into account SOC variation, and the alternative method, which includes SOC fixation from RPD. SC1 shows 0.57% growth in Gross Domestic Product (GDP) and 0.71% in real household consumption relative to the 2035 baseline. There would be a social return of R$85.8 billion (in 2022 prices), representing R$8.31 for every real invested. Cattle ranching would expand production using less area, resulting in a land-saving effect of 972.6 thousand hectares in 2035. GHG emissions would increase by 9.3% in the original accounting method, resulting from herd and activity level growth. In the alternative method, 0.16% mitigation of emissions would occur, showing that SOC fixation can more than offset the economic activity growth. Brazil's mitigation levels would be higher in 2025 and 2030 (42.86% and 38.89% respectively), but still not enough to meet the 2030 NDC target.

Keywords: Paris Agreement, Greenhouse Gases, Low carbon agriculture, Soil organic carbon, Computable General Equilibrium.

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Introduction

Historically the land use, land use change, and forestry (LULUCF) sector are the largest source of Brazilian greenhouse gases (GHG) emissions. However, in 2016 agriculture took the lead with a 36% share, compared to approximately 26% arising from LULUCF. Since the 15th Conference of the Parties (COP-15) of the United Nations Framework Convention on Climate Change (UNFCCC) Brazil has presented commitments to promote sustainable production systems in agriculture (SPS) aiming the mitigation of GHG emissions and climate change (Brazil, 2012). At COP-26, the country amplified its Nationally Determined Contribution (NDC) to reduce 50% of GHG emissions by 2030 compared to 2005 levels (Brazil, 2022).

As methane emissions in cattle ranching are one of the main GHG emissions sources, among the SPS promoted by Brazil is the degraded pastures recovery (recuperação de pastagens degradadas - RPD), with a target of 30 million hectares (Mha) for 2030 (Brazil, 2022), representing the continuation of COP-15 actions that promoted the RPD of 26.8 Mha[3] between 2010 and 2020 (Brazil, 2021). The cattle ranching intensification, in general, has occurred since the 1980s (Gasques et al., 2016; Martha et al., 2012; Vieira Filho, 2018) and from 1990 to 2016 Brazil reduced enteric fermentation GHG emissions per head of cattle and methane emissions per liter of milk by 8% and 58%, respectively (Brazil, 2021). However, in 2020 there were still about 89 Mha of pastures in the intermediate or severe degradation stages (55.35% of Brazil's pastures) (Laboratório de Processamento de Imagens e Geoprocessamento - Lapig, 2022). This occurs because the traditional pasture management system in Brazil is the extensive form, with low input usage and productivity, associated with high GHG emissions coefficients per unit of product (Dias-Filho, 2012; Teague et al., 2011; Vieira Filho, 2018).

Despite the various climatic (precipitation and temperature), biophysical (soil and topography), genetics (age, gender, race, and stage of development), animal nutrition, and other factors that influence GHG emissions from livestock (Intergovernmental Panel on Climate Change - IPCC, 2019), RPD is pointed out as a strategy that enables greater SOC fixation and can be associated with improvements in management systems that also result in a reduction in the intensity of GHG emissions from livestock, in some cases even allowing "net zero" emissions (Alves et al., 2015; Damian et al., 2021; de Figueiredo et al., 2017; Eri et al., 2020; Thornton & Herrero, 2010). Sanderman et al. (2020) estimated SOC stock changes under RPD scenarios, highlighting that Brazil could achieve SOC sequestration between 1,906 to 3,483 tera gram of carbon dioxide (Tg CO2eq) in 20 years, or 120% to 220% relative to Brazil's total emissions in 2016. The Paris Agreement itself showed the intention to increase the SOC stock by 0.4%, which could result in annual mitigation of between 20% and 35% of all anthropogenic emissions (Minasny et al., 2017). Therefore, to mitigate GHG emissions in the RPD, the SOC is a key component. In spite of that, this contribution has not yet been formally considered in Brazil's communications to the UNFCCC (Brazil, 2021).

Even with IPCC (2019) guidelines regarding SOC, the dynamics of SOC stock change is still discussed in the literature, where studies in the Brazilian biomes highlight the possibility of both expansion or reduction of SOC in the conversion of native vegetation to pasture. For Assad et al. (2013), Desjardins et al. (1994), and Groppo et al. (2015), pastures cause a reduction in SOC compared to native vegetation. Cerri et al. (2004; 2007), de Moraes et al. (1996), Desjardins et al. (2004), and dos Santos et al. (2019), estimate expansions of this stock. Braz et al. (2013), Carvalho et al. (2010), Fearnside & Barbosa (1998), and Maia et al. (2009), point out the possibility of both cases depending mainly on the pasture management system, where the well-managed pastures present SOC fixation, while the degraded pastures release SOC. For SOC fixation to mitigate GHG emissions, Cerri et al. (2007) highlight the importance of effectively recovering pastureland instead of expanding its area, since deforestation results in the reduction of carbon stock in trees (above-ground carbon), which would not be compensated by the SOC fixation.

Computable General Equilibrium (CGE) models have been used to evaluate the systematic effects of environmental policies in Brazil, which reflect on fiscal policy, land use, and productivity, among other factors. As Brazil presents a territory of continental dimensions, which results in relative heterogeneity in soil quality, topography, precipitation, temperature, and other characteristics that provide high biodiversity of fauna and flora (Fornazier & Vieira Filho, 2012), systematic methods can be even more important to highlight regional differences of RPD effects.

Ferreira Filho & Horridge (2016) evaluating changes in the Brazilian Forest Code showed that increasing pasture productivity would result in positive macroeconomic effects, but increase GHG emissions since no

[3] Considering both restoration and degraded pastures area decrease – transitions to other uses.

GHG emissions change of cattle ranching with the technological improvement was incorporated in the modelling. In none of the author's scenarios, Brazil would achieve the NDC targets for 2030. Souza et al. (2020) also showed positive macroeconomic impacts of RPD from 2015 to 2025 but did not measure environmental effects. Stocco et al. (2020) when considering that a 1% increase in land productivity resulted in 0.0043% GHG emission mitigation from beef cattle ranching[4], showed mitigation of Brazil's emissions of 18.29% and a land-saving effect of 0.88 Mha from the RPD of 66 Mha. However, the authors did not compare the national results with the NDC targets.

This paper evaluates the impacts of degraded pastures recovery in Brazil on socioeconomic aspects and on GHG mitigation targets of the Nationally Determined Contribution (NDC). For the impacts on emissions two carbon accounting methods were considered, the original method of Brazil's emissions inventory, which does not take into account SOC variation, and the alternative method, which includes SOC fixation from RPD. It brings new calibrations of regional parameters of RPD in productivity, investment and GHG emissions for beef and dairy cattle in Brazil, based on the most recent technological structure data of the Brazilian economy (2015). This study incorporates these changes in modeling, and seeks to bring new contributions to the topic by explicitly considering the role played by the SOC fixation arising from RPD (both from beef and dairy cattle), from the 2015 to 2035 period.

Methodology

We used a computable, dynamic, inter-regional, and bottom-up general equilibrium model, called TERM-BR15, simulating three scenarios for the period 2015 to 2035. We calibrated the model for 2015, and it is based on previous versions presented by Ferreira Filho & Horridge (2006a, 2006b). We used the most recent information available from the Brazilian Input-Output Matrix (Brazilian Institute of Geography and Statistics - IBGE, 2018), the Annual Social Information Report (RAIS) (Brasil, 2016a), ComexStat (Brasil, 2015), among others surveys. The model was calibrated for 122 products and industries, presenting 10 representative household types[5] (income classes) and 10 work types (wage as a proxy for qualification).

Since TERM-BR is a dynamic model, it is possible to analyze the trajectory of the economy over a period of policy implementation. In this case, capital accumulation and investment over time are endogenously determined. It is an inter-regional and bottom-up model, where Brazil's economy is disaggregated into its 27 federative units, obtaining a particular result for each region, with the integration of these economies by an inter-regional trade flow and by the factor market. The aggregation of these individual results generates impacts at the national level. In inter-regional trade deficits are possible, household consumption is associated with regional income, there is inter-regional mobility of the labor factor according to changes in the relative real wage, and the demand of users for products from other regions occurs in fixed proportions.

For the simulation of the baseline and policy scenarios, we aggregated Brazil's 27 states into 14 regions, accordingly to the representativeness and importance for livestock production (Table 1, Figure 1). The 122 products were aggregated into 38 products; however, the agricultural products were kept disaggregated (Appendix Table 1). This aggregation procedure is key to reducing the computational costs of solving the model and the analytical complexity of the results.

[4] Dairy cattle were not included.

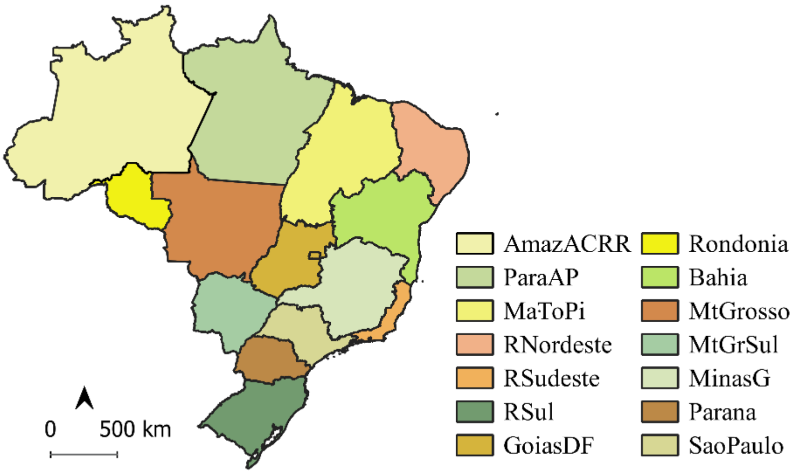
[5] We used the income elasticities of consumption for the 10 representative households with data from Hoffmann (2010).

Table 1. TERM-BR15 aggregation of the Brazilian states

TERM-BR15 regions	Brazilian states	Macro regions
Rondonia	Rondônia	
AmazACRR	Acre, Amazonas e Roraima	North
ParaAP	Pará e Amapá	
MaToPi	Maranhão, Tocantins e Piauí	North/Northeast
RNordeste	Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas e Sergipe	Northeast
Bahia	Bahia	
MinasG	Minas Gerais	
RSudeste	Espírito Santo e Rio de Janeiro	Southeast
SaoPaulo	São Paulo	
Parana	Paraná	South
RSul	Santa Catarina e Rio Grande do Sul	
MtGrSul	Mato Grosso do Sul	
MtGrosso	Mato Grosso	Mid-West
GoiasDF	Goiás e Distrito Federal	

Source: authors.

Figure 1. Spatial location of the TERM-BR15 regions



Source: authors.

The model also presents two modules of GHG emissions, one linked to productive activities and fuel and the other related to LULUCF, accounting for GHG emissions from land use transitions, the available land stock, and the deforestation rate, for 4 broad land use categories (Agriculture, Pastures, Planted Forests, Native Vegetation), 6 Brazilian biomes and 27 regions.

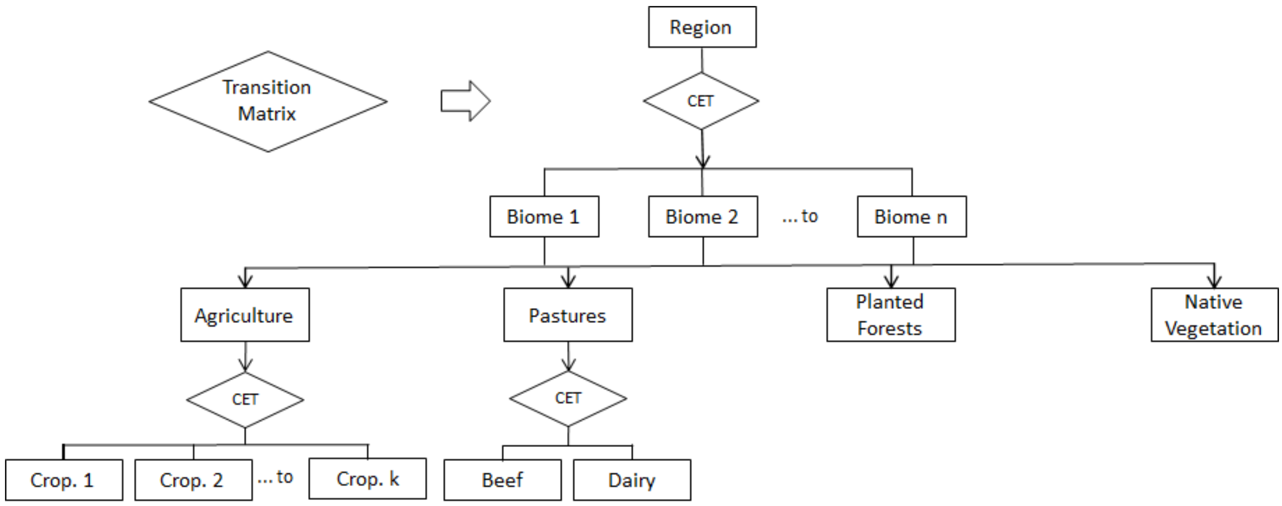
The first module was based on information from the System of Estimates of Emissions and Removals of Greenhouse Gases - SEEG (2019), for the year 2015 and the methodology proposed by Ferreira Filho & Rocha (2008) and Santos & Ferreira Filho (2017). The emissions are disaggregated by 14 types of gases and converted to CO_2eq using the Global Warming Potential (GWP) developed by the IPCC fifth report (AR5) (SEEG, 2019).

For the second module, we used information from Brazil (2016b) provided by the National Emissions Registry System (SIRENE), regarding the land use transition matrices (2002-2010) and net emissions (2002-2010). The original 15 land use categories were aggregated into 5 categories: agriculture, pastures, planted forests, native vegetation, and a residual category. Then we build specific matrices for each Brazilian state (27) and Brazilian biomes (Amazonia, Cerrado, Caatinga, Atlantic Forest, Pampa, and Pantanal). Alternatively, the native vegetation category and the residual one can be aggregated.

From the land use matrices, we estimate the probability of land use change between the category's agriculture, pasture, planted forests, and native vegetation from a given year to the following year, as well as the GHG emission coefficients associated with these changes (Figure 2). This process is specific by region and biome. Land supply in any year is given by the transition matrix, but it can suffer endogenous impacts due to technological changes and the economic rate of return of activities in the different land uses and regions. Thus, the transition matrices determine the total available land for each land use category, biome, and year (Ferreira Filho et al., 2015).

After the transition matrix, the distribution of land uses to the activities is done by assigning the crops, livestock and planted forest products to the agricultural, pasture and planted forest areas, respectively, according to the activities rate of return differences in each land use and CET function.

Figure 2. Land use transition matrix



Source: authors.

Simulation strategy

The RPD causes a productivity increase in the livestock activity (beef and dairy) and SOC fixation, requiring for its implementation a certain volume of investments. From the socioeconomic point of view, the change in productivity can influence the volumes produced and their relative prices, impacting all macroeconomic aggregates. These changes also affect land use, which in turn has implications for GHG emissions.

We did the policy shocks projecting the observed annual rate of degraded pasture recovery from 2010 to 2020 for the simulation period (2015 to 2035) (Lapig, 2022), the investments for RPD projected with the values per hectare financed by rural credit (BACEN, 2022), the increases in productivity of cattle ranching (beef and dairy, without distinction)[6] due to pasture recovery from Rocha Junior et al. (2022)[7], the elasticity of productivity-GHG emissions was calculated from the relation of Sanderman et al. (2020) SOC projections and the aforementioned increase in productivity. The regional impacts of RPD on livestock productivity and

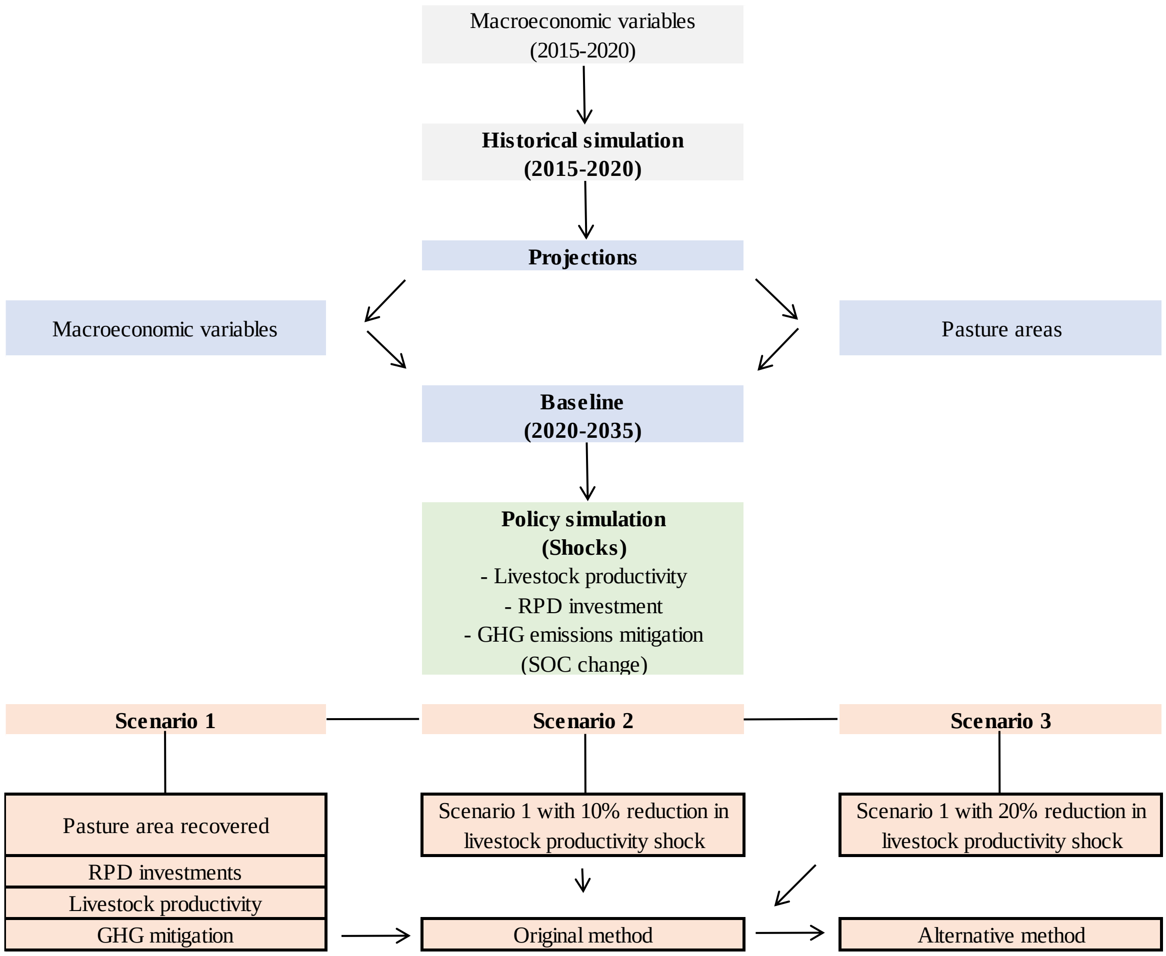
[6] As the shocks are applied to land productivity, the difference in the production structure between beef and dairy cattle ranching activities result in different impacts on the CGE model. The disaggregation of beef and dairy cattle ranching into different products according to their technological level is at the frontier of development of general equilibrium models. This is a limitation of the present research, which considers impacts in terms of a single product, with effects around investment and productivity, without exogenous shocks of changes in cost structures resulting from RPD.

[7] The econometric estimation controls for municipal characteristics that go beyond purely biophysical or stocking rate effects, but rather allocative and efficiency effects, in order to indirectly portray the Brazilian municipalities heterogeneity of the livestock production systems, later aggregated to the states of Brazil.

regional productivity-GHG emissions elasticities, to the best of the authors' knowledge, are unprecedented data in the assessment of the Brazilian NDC.

We simulated three scenarios: i) Scenario 1 (SC1) RPD including shocks of livestock productivity, investment, and GHG mitigation impacts of SOC stock growth; ii) Scenario 2 (SC2), SC1 with 10% reduction of productivity shocks; iii) Scenario 3 (SC3), SC1 with 20% reduction of productivity shocks. SC1 represents the main simulation, while the other two scenarios are sensitivity analyses. The scenarios allow the comparison of GHG emissions results considering or not the SOC fixation, results without the inclusion of this benefit are called the "original method" (according to the Brazilian GHG inventory methodology) while accounting for mitigation effects is called the "alternative method". The simulation strategy is presented in Figure 3.

Figure 3. Simulation strategy



Source: authors.

Baseline

We projected a baseline to portray the dynamics of the Brazilian economy, land use, GHG emissions, and other aspects, without RPD impacts. We updated the base year from 2015 to 2020 with a historical simulation of the land use changes, GDP, household consumption, government consumption, investment, exports and imports of goods and services, and population. In sequence, macroeconomic variables and total pasture areas up to 2035 are projected, without considering productivity shocks or GHG mitigation from RPD.

The land use and land use change analysis for the RPD impact assessment relies on two main aspects for the baseline projection, the change in the native vegetation area (deforestation or reforestation) and in the pasture area. Native vegetation area follows the original transition matrix. The pasture area was projected by a historical simulation of the behavior observed from 2015 to 2020 with satellite observation data from Lapig

(2022). From 2021 to 2035, the pasture area was projected through the average change observed from 2010 to 2020 (Lapig, 2022)[8].

Policy shocks

We used the average observed values of non-degraded and degraded pastures of the 2010 to 2020 period from satellite image data of Lapig (2022) to project the annual rate of RPD in the Brazilian regions[9]. After projecting the RPD area, we used data from the Banco Central do Brasil - BACEN (2022) of the average investment per hectare from the ABC Program credit lines for RPD from 2015 to 2021 by the Brazilian regions.

The product of average investment per hectare and the projection of the RPD area results in the total increase in investment, which divided by the base year (of the model) investment in the livestock activity represents the percentage ratio of increase in cattle ranching and dairy cattle investment from RPD, for each Brazilian region[10]. This indicator is recalculated annually according to the stock change of investments (i.e., the policy shock is decreasing according to the investment stock increase in livestock production).

We used an estimate of the marginal productivity effect of replacing degraded pasture area with non-degraded pasture area for beef and dairy cattle ranching activities using a distance function, with information from the 2017 Agricultural and Livestock Census, carried out by Rocha Junior et al. (2022), at the municipal level and aggregated for the Brazilian regions. The estimate considers the effect of the substitution of the degraded pasture input for pasture in good conditions, controlling for municipal characteristics that go beyond purely biophysical or animal stocking rate effects, but rather allocative and efficiency effects of the livestock production systems in the Brazilian municipalities (Rocha Junior et al., 2022).

The productivity shock calculation presents three steps: i) obtaining the total effect of increasing Gross Production Value (GPV) through the RPD area for each Brazilian region; ii) calculating the new estimated productivity level by the Brazilian regions; iii) calculating the percentage increase in productivity per Brazilian region for the shock in the TERM-BR15 simulation. This indicator is recalculated annually according to the productivity level change.

The annual rate of RPD, the average annual percentage shock[11] of investments, and productivity in cattle ranching (beef and dairy cattle) for the simulations period (2020-2035) are presented in Table 2. The differences in RPD's productivity shocks on the territory are due to the particularities of regional production structures. Therefore, this is a result of the regional heterogeneity in the ratio of input use per output, as well as to qualitative aspects of the rural environment (education, technical assistance, agricultural aptitude), so that the RPD presents different impacts on production efficiency (Rocha Junior et al., 2022).

In the Brazilian states where there was a reduction in the good quality pasture area (Paraíba, Pernambuco, Alagoas, Sergipe, and Paraná), we observed a proportionally greater decrease in the total pasture area. Thus, the reduction in the good quality pasture area may have been caused by the agricultural transition, rather than the "degradation" of pastures. Therefore, shocks as if there had been pasture "degradation" could present biases in relation to the processes effectively observed, which is why negative productivity shocks were dropped, keeping the productivity at its original level.

[8] We also applied a geometric progression to curb the decrease in pasture areas. We implemented this procedure because despite the reduction of pastures areas from 2010 to 2020, if we consider the interval from 2000 to 2020 the pasture area remained practically constant, and analyzing the expansion of the deforestation rate after 2012 (INPE, 2021) we estimate that it will not be possible to maintain in the long term the agricultural transition dynamics observed from 2010 to 2020.

[9] The percentage pasture recovery change as the good quality pasture stock changes over the simulation period.

[10] For Amapá, Ceará and Rio Grande do Norte, which do not have a historical average for the ABC Program, we used the average for the North and Northeast regions, respectively.

[11] The percentage shocks to investment and productivity are calculated annually, so the shocks are larger initially and decrease as aggregate investment and productivity in livestock and raw milk accumulate, but the areas of pasture recovered annually do not change. The table presents the average value (linearized) of investment and productivity shocks only for simplification.

Table 2. Annual RPD, investment and productivity shocks

Region	RPD (1,000 ha)	Investment shock (% p.y.)	Productivity shock (% p.y.)
Rondonia	71	3,03	2,02
AmazACRR	46	8,71	2,40
ParaAP	108	1,33	1,47
Bahia	110	1,14	1,37
MaToPi	195	2,99	2,35
RNordeste	33	0,75	0,77
MinasG	96	0,72	0,67
SaoPaulo	25	0,84	1,34
RSudeste	19	0,94	1,00
Parana	0	0	0
RSul	106	2,85	2,54
MtGrSul	73	0,33	1,08
MtGrosso	262	1,71	2,30
GoiasDF	162	0,85	1,93
Brazil	1304	1,72	0,99

Source: authors.

Productivity-GHG emissions elasticity in cattle ranching from RPD

Sanderman et al. (2020) estimated SOC change from LUC using parameters provided by the IPCC (2019), which account for factors related to pasture degradation stage, organic input management, soil types, and climate. The methodology considers that the effects of SOC changes occur linearly from 2018 to 2038, a 20-year period. We used these data in the simulation for the period 2015 to 2035, compatible with the NDC period, allowing us to analyze the impacts of SOC on compliance with the Brazilian PNMC.

Sanderman et al. (2020) present several scenarios, but we selected a conservative option of pastures partial recovery, which comprises the degraded pastures recovery for high intensity grazing systems. To calculate the SOC change we used the data from Sanderman et al. (2020) for the territory with pasture areas identified by Lapig (2022). The total SOC change effect over the 20-year period was transformed into an annual GHG mitigation factor. Using the ratio of this annual mitigation to GHG emissions per hectare of pastures with TERM-BR15 data GHG emissions for beef and dairy activities, we obtain the percentage of GHG mitigation resulting from the RPD each activity.

Following this, we used the estimated increase in productivity to obtain the elasticity of productivity-GHG emissions. Table 3 presents for each Brazilian region the impact on GHG emissions resulting from a 1% increase in productivity, that are in general mitigation of emissions (negative sign on the elasticities). It is important to note that there is still uncertainty in the estimates of SOC change, thus Sanderman et al. (2020) recommend caution in using the data. According to the authors, the methodology is not appropriate for territorial analysis at a very specific level, which is not the case of the proposal of this research, since TERM-BR15 is disaggregated for Brazilian regions, which represent large territorial extensions.

We must also consider that besides the SOC change, several factors impact the GHG emission coefficients of dairy and beef cattle production, which may or may not be affected by RPD, as mentioned before regarding IPCC (2019) data. RPD may be associated with changes in feed digestibility, in herd composition, and other components beyond those estimated by Sanderman et al. (2020). Thus, there may still be complementary GHG mitigation or increase effects depending on the observed changes, which were not included in this study due to lack of information.

Table 3. Elasticity of productivity-GHG emissions

Region	Beef	Dairy
Rondonia	-0.002	-0.004
AmazACRR	-0.001	-0.003
ParaAP	-0.002	-0.012
Bahia	-0.030	-0.052
MaToPi	-0.060	-0.122
RNordeste	-0.039	-0.025
MinasG	-0.070	-0.020
SaoPaulo	-0.011	-0.009
RSudeste	-0.063	-0.024
Parana	-0.021	-0.009
RSul	-0.074	-0.047
MtGrSul	-0.021	-0.153
MtGrosso	-0.019	-0.100
GoiasDF	-0.014	-0.012

Source: authors results.

Macroeconomic closure

Aggregate capital is calculated endogenously, depending on the dynamics of investment and depreciation. Investment in sectors and regions is conditioned by the endogenously determined rate of return on capital so that the capital stock change impacts the remuneration of this production factor. Only in the policy simulation, the closure was modified so that in the beef and dairy cattle sectors investment is exogenous, with the shock determined by the volume of investments required for the estimated RPD area. Therefore, investments for RPD come from the reallocation of investments from other sectors.

This premise is justified due to the existence of credit mechanisms for financing the low carbon agriculture in Brazil, which means an option to finance cattle ranching at the expense of other activities. Beyond that the volume of resources needed is small, given that of the R$ 236.31 billion of Rural Credit projected for the 2020/21 Crop Year, only R$ 2.5 billion were destined for Program ABC (low carbon agriculture), representing less than 1.1% (Brazil, 2020). Thus, no changes in the tax structure, savings rate, or external financing mechanism were considered to implement the policy.

The land uses are considered endogenous, except for the pasture area in the consolidated regions (Northeast, Southeast, São Paulo, Paraná, and South regions), where we assumed that the areas available for expansion of the agricultural and pasture area were used up. Real household consumption is endogenous according to changes in regional income. Real government consumption is also endogenous, following changes in real household consumption.

Results and discussions

RPD would provide Gross Domestic Product (GDP) growth of 0.57%, relative to the 2035 baseline[12] (Table 4). Thus, there would be a social return of R$85.8 billion (in 2022 prices), representing R$8.31 for every real invested, a (real) rate of return of 16.04% per year. The sensitivity scenarios[13] showed that the impacts are consistent, maintaining reasonable direction and proportion compared to the decreases in productivity shocks,

[12] All the results analyzed are percentage differences from the baseline, even if the expression of this methodological detail is omitted.
[13] Sensitivity scenarios isolating the effect of productivity or investment were carried out, showing that the impact of investments alone was small compared to the productivity shock. For this reason, only the joint effect of both shocks was presented.

therefore we will only present the results of SC1. Table 4 also shows the macroeconomic results for 2025 and 2030, periods that correspond to the Brazilian NDC targets. The 2030 GDP result presents a difference of 0.02 percentage points (4.6% lower) of the impact found by Stocco et al. (2020)[14], even though these authors have considered the RPD of 66 million hectares, compared to 13 million hectares in the present simulation.

Table 4. Macroeconomic variables. Percentage cumulative change in 2025, 2030, and 2035 from the baseline

Variable	2025			2030			2035		
	SC1	SC2	SC3	SC1	SC2	SC3	SC1	SC2	SC3
Real household consumption	0.29	0.26	0.23	0.53	0.48	0.43	0.71	0.65	0.59
Exports (volume)	0.12	0.11	0.10	0.32	0.29	0.25	0.65	0.58	0.52
Imports (volume)	0.20	0.18	0.16	0.66	0.60	0.53	1.00	0.90	0.81
Real GDP	0.23	0.21	0.19	0.41	0.38	0.34	0.57	0.52	0.47
Real wage	0.35	0.32	0.28	0.66	0.61	0.55	0.91	0.83	0.76

Source: authors results.

In scenarios with joint policies to reduce deforestation and livestock intensification from 2015 to 2030, Ferreira Filho & Horridge (2016) showed that the RPD of 15 Mha would provide an increase in real GDP between 0.365% and 0.157% in 2030. Souza et al. (2020) estimated for the 2015 to 2025 period a 0.4% GDP reduction if RPD was not used, in this case a more intense effect than the growth estimated by the present research of 0.23%. However, it is noteworthy that the estimation of productivity growth by an economic model, controlling the socioeconomic and biophysical aspects of the technological structures of cattle ranching at the municipal level, makes it possible to analyze productivity changes in a more specific way, translating them into monetary terms, unlike the exclusively biophysical model used by the aforementioned authors[15].

Real consumption for all household classes would increase in 2035, with an aggregate result 0.71% higher than the baseline (Table 4). Productivity gains linked to the agricultural and livestock sector would increase exports in SC1 by 0.65% in 2035, concomitantly with import growth of 1.0%, given the aforementioned increase in income (Table 4). Exports increase even with an exchange rate appreciation of 1.02%, due to gains in productivity and production resulting from the release of production factors from beef and dairy cattle to other activities, especially the reduction in the pasture area of dairy cattle[16].

In regional terms, the reallocation of investments from other activities to cattle ranching would benefit those regions with higher cattle production and productivity shocks, such as the Center-West and North of the country (Table 5). This, however would reduce the level of investments and activity in more developed and diversified economies, such as the Southeast region. Even so, the real GDP would increase in all regions, with the exception of São Paulo where a decrease of 0.06% would occur. The results were different from those obtained by Stocco et al. (2020) in which the entire Southeast region would register reductions in the real GDP.

The impacts of cattle ranching productivity growth on agricultural and livestock production initially occurs by expanding production of beef and dairy cattle. This increase accompanies the reduction in prices of the beef (27.3%) and dairy cattle products (33.4%). However, the effect of increasing the quantities produced would be capable of overcoming the price reduction, expanding the beef and dairy cattle productions in 2035 by 27.88% and 9.61%, respectively (Table 6). The decrease in cattle ranching prices would also have impacts on the other activities in the chain of production, increasing the competitiveness of sectors such as slaughter and meat processing, causing a 15.44% growth in production by 2035 (Table 6).

The increase in livestock productivity would allow production to be expanded using fewer inputs and primary factors (land, capital, and labor) freeing them for other activities, resulting in new effects on prices and quantities produced. Sugar cane, pork, poultry and eggs would present an increase in production of 0.36%, 9.44%, 6.34%, respectively. The first product (sugar cane), given the higher demand for fuel accompanying the economic growth. The production of pork, and poultry and eggs would take advantage of both economic

[14] The authors evaluated the impacts exclusively on beef cattle ranching, while this research also included dairy cattle.
[15] Other authors such as Gurgel & Laurenzana (2016) and Fundação Getúlio Vargas (2017) have not addressed the 2020 to 2030 period. Research such as by Gurgel et al. (2019), La Rovere et al. (2018), and Machado et al. (2020) do not allow analyses of macroeconomic outcomes of RPD in a comparable way.
[16] The impacts on land use will be commented on later in Table 7.

growth and the release of resources from cattle ranching. In this case, slaughter would increase the intermediate consumption of raw materials (cattle, pork, and poultry) by 4.79%, for a 15.44% production increase.

Table 5. Regional beef and dairy cattle data and macroeconomic impact. Percentage cumulative change in 2035 from the baseline.

Regions	Beef and dairy cattle of regional production (%)	Beef and dairy cattle productivity shock	Real household consumption	Real GDP
Rondonia	7.8	23.85	2.59	5.11
AmazACRR	1.4	30.37	1.63	0.85
ParaAP	3.5	16.04	0.74	1.51
Bahia	1.5	14.79	-0.33	0.43
MaToPi	3.4	27.72	1.06	2.14
RNordeste	1.3	8.33	-0.04	0.27
MinasG	1.5	6.61	0.57	0.53
SaoPaulo	0.1	12.05	0.36	-0.06
RSudeste	0.2	9.5	0.45	0.04
Parana	0.8	0	1.43	0.73
RSul	0.9	27.83	2.12	1.07
MtGrSul	4.5	10.8	0.6	2.15
MtGrosso	5	26.49	1.55	4.52
GoiasDF	2	21.22	0.33	1.05

Source: authors results.

As mentioned earlier, regionally cattle ranching production increases are directly related to productivity growth. In this manner, regions such as AmazACRR, RSul, MaToPi, Mato Grosso, Rondônia, and GoiasDF registered increases in beef cattle production greater than 35%, and dairy cattle production greater than 15%, compared to 28.9% and 9.6%, respectively, in Brazil total (Table 6).

Table 6. Regional beef, dairy cattle, and slaughter production. Percentage cumulative change in 2035 from the baseline.

Regions	Beef	Dairy	Slaughter
Rondonia	35.43	15.18	17.67
AmazACRR	49.13	20.62	-0.89
ParaAP	23.67	6.73	5.61
Bahia	19.11	9.62	-5.48
MaToPi	43.47	21.99	3.57
RNordeste	13.53	1.82	-3.66
MinasG	6.26	3.82	6.06
SaoPaulo	23.08	12.44	17.84
RSudeste	17.31	6.32	13.61
Parana	1.58	-5.67	18.27
RSul	49.53	23.57	20.62
MtGrSul	15.24	4.37	11.43
MtGrosso	40.92	22.07	21.35
GoiasDF	33.55	20.84	-4.88
Brazil	27.88	9.61	15.44

Source: authors results.

The land productivity growth in dairy cattle would free up pasture areas for beef cattle, and also for other activities, reducing the total pasture area by approximately 1.4 Mha for dairy cattle, while beef cattle areas remain practically constant (Table 7). This land competition for beef and dairy cattle is especially important in the Northeast, São Paulo, RSudeste, Paraná, and Rsul regions, where as presented earlier, it is necessary to fix the total pasture areas in view of the depletion of the agricultural frontiers of these regions.

Agricultural areas would increase by 0.33 Mha, planted forest areas by 0.06 Mha and native vegetation by 0.97 Mha. The growth of the agricultural and planted forest areas would occur only in the states where there was a total reduction of pastures (Bahia, Minas Gerais, Mato Grosso do Sul and GoiasDF) registering an increase of approximately 488,000 hectares of these areas, i.e., the other regions would register a decrease of 89,000 ha of agricultural and planted forest areas.

In this context, cattle ranching intensification and the reduction in product prices have the effect of avoiding national deforestation of 0.97 Mha. However, in the regions AmazACRR ("Amazonas, Acre and Roraima"), and MaToPi ("Maranhão, Tocantins and Piaui"), agricultural frontiers, the absolute area of pastures would increase in the deforestation, where native vegetation would decrease by 0.2 Mha and 0.12 Mha, respectively (Table 7).

Table 7. Regional pasture (beef and dairy cattle activities) and native vegetation LUC. Percentage and thousand hectares cumulative change in 2035 from the baseline.

Regions	Percentage change			Thousand hectares change		
	Beef	**Dairy**	**Native vegetation**	**Beef**	**Dairy**	**Native vegetation**
Rondonia	1.18	-13.95	0.06	73	-80	9
AmazACRR	5.80	-14.43	-0.10	267	-66	-195
ParaAP	0.33	-13.42	0.10	45	-167	123
Bahia	-2.56	-10.33	0.97	-288	-100	349
MaToPi	1.93	-13.33	-0.21	327	-164	-124
RNordeste	0.85	-9.55	0	62	-62	0
MinasG	-4.27	-6.47	1.85	-701	-93	542
SaoPaulo	0.76	-7.95	0	25	-25	0
RSudeste	0.60	-8.82	0	14	-14	0
Parana	0.87	-6.33	0	26	-26	0
RSul	1.92	-15.78	0	158	-158	0
MtGrSul	-1.19	-10.51	1.41	-183	-138	159
MtGrosso	1.06	-12.46	0.09	220	-222	43
GoiasDF	0.17	-9.37	0.56	21	-124	67
Brazil	0.05	-11.19	0.17	67	-1439	973

Source: authors results.

Even in the presence of exchange rate appreciation, there would be an increase in beef cattle and meat exports in Brazil, of 324.9% and 32.3%, respectively, with increases in all regions. Despite the model results of an increase in beef cattle exports, only 1.1% of cattle output was exported in 2020, presenting a low impact on total exports. While for slaughter and meat processing this share was 32.3%. This growth in Brazil's participation in the meat market is projected by the United States Department of Agriculture (2022), estimating that among the main meat exporters, Brazil would account for 50% of the increase in exports by 2031.

For all agricultural crops, with the exception of a bundle of permanent crops, we would observe an increase in exports. Coffee, soybeans, corn and cotton, and rice would register export growth of 2.0%, 0.66%, 0.60%, and 0.17%, respectively. These crops would present production growth as a result of the land release from cattle ranching, and the efficiency gains downstream of the industrial chains would cause a reduction in intermediate consumption, redirecting crop production to the external market. Also, crops like coffee, soybeans, and corn are destined more than 70% to exports, than household consumption growth has little impact.

Regionally, there would only be reductions in exports of coffee, soy, and corn where the production of these decreased due to the greater increase in productivity in cattle ranching and the destination of agricultural areas to pasture, such as Rondônia, AmazACRR, MaToPi, and Mato Grosso. In the case of rice, there would be an increase in exports mainly in Paraná and RSul which represented more than 75% of the Brazilian production in 2020.

After addressing the effects on production, land use, and exports, we return to the impacts on household consumption. The RPD impacts households as an income effect from economic growth, with the price reduction, and finally, the reallocation of productive resources could imply, as in the case of cattle ranching, a decrease in the demand for labor. The results show that the income effects of economic growth and price reduction would outweigh the effects of reduced labor demand in cattle ranching, resulting in higher real consumption in Brazil for all classes of households (income classes) (Table 8).

Table 8. Regional real household consumption by family classes. Percentage cumulative change in 2035 from the baseline.

Regions	**POF1**	**POF2**	**POF3**	**POF4**	**POF5**	**POF6**	**POF7**	**POF8**	**POF9**	**POF10**
Rondonia	1.57	2.58	2.45	2.36	2.45	2.14	2.33	2.37	2.54	3.10
AmazACRR	5.36	2.61	1.88	1.62	1.35	1.05	1.03	0.80	0.71	0.52
ParaAP	0.94	0.88	0.77	0.75	0.68	0.60	0.73	0.72	0.77	0.67
Bahia	-1.90	-0.52	-0.35	-0.25	-0.26	-0.25	-0.17	-0.24	-0.07	-0.15
MaToPi	1.92	1.17	0.98	0.84	0.92	0.83	0.98	0.82	0.93	1.07
RNordeste	-1.63	-0.22	-0.07	-0.03	-0.07	0.03	0.13	0.09	0.25	0.46
MinasG	-1.11	0.22	0.18	0.24	0.97	0.41	0.49	0.62	0.61	0.83
SaoPaulo	0.47	0.64	0.66	0.74	0.49	0.39	0.31	0.41	0.27	0.24
RSudeste	0.24	0.41	0.66	0.52	0.51	0.53	0.53	0.73	0.57	0.32
Parana	1.61	2.06	1.62	1.65	1.47	1.27	1.27	1.38	1.28	1.33
RSul	1.57	1.60	1.62	1.62	1.70	1.65	1.94	1.99	1.93	2.63
MtGrSul	1.30	-0.20	0.03	0.06	0.07	0.21	0.41	1.09	0.54	1.14
MtGrosso	2.30	3.19	1.97	1.56	1.27	0.89	0.83	0.89	0.91	1.37
GoiasDF	0.18	0.15	-0.01	-0.02	-0.05	0.01	0.31	0.13	0.32	0.70
Brazil	0.01	0.56	0.62	0.71	0.73	0.64	0.70	0.75	0.69	0.79

Source: authors results. POF1 to POF10 are income classes from lowest to highest.

Household consumption impacts would be approximately 46.6% higher for the three wealthiest family classes than for the three poorest family classes (average 0.75 p.p. versus 0.40 p.p. increase, Table 8). The richest families have a larger share of imported products then are more benefited by the exchange rate appreciation, and provide less low-skilled labor, and thus are less impacted by the reduction of labor demand on cattle ranching.

Regionally, the largest reductions in real household consumption occur in POF1, in the Bahia, Northeast, and Minas Gerais regions (Table 8). These regions present a share of less qualified labor in cattle ranching above the average for Brazil. The conditions are different for a region like MaToPi, that despite the 19% share of less qualified labor in cattle ranching, would present the third highest growth in beef cattle (43.47%) and dairy cattle (21.99%) production so that the multiplier effects on income would compensate for the reduced demand for labor in livestock activities.

Environmental impacts

The second set of relevant RPD effects are environmental, which are related to externalities on air pollution, water resources, biodiversity, and LUC. Currently, it is only possible to analyze GHG emissions and LUC through the TERM-BR15 model. For LULUCF, the main effect refers to deforestation or the maintenance of native vegetation. The literature is uncertain about the impacts of agricultural productivity on LUC, a controversy marked by the dichotomy between the Borlaug effect (Borlaug, 2002) and the Jevons effect (Jevons, 1866).

Borlaug effect establishes that the increase in land productivity causes a land-saving impact, as the shift in the production possibility frontier allows a higher level of output with the same quantity of inputs. On the other hand, the Jevons effect assumes that the increase in agricultural productivity would provide an increase in profitability, so it would encourage increases in production, thus increasing LUC from native vegetation to agricultural lands. As mentioned earlier RPD would result in the Borlaug effect, decreasing the deforestation by approximately 1 Mha, relative to the 2035 baseline, providing mitigation of GHG emissions related to LUC of 1,303 Gg CO2eq (-0.53%) (Table 9).

It is also noteworthy that the impacts on LUC and GHG emissions did not behave linearly, with a reduction in the GHG emission mitigation from LUC throughout the simulation period. All biomes would present a constant decrease in deforestation, with the exception of the Amazon biome, responsible for the mentioned peculiarity in the behavior of GHG emissions from LUC, given the higher intensity of carbon in the native vegetation of this biome in relation to the others. The increase in deforestation occurred exclusively in the AmazACRR and MaToPi regions - agricultural frontiers - which would see a transition from agricultural areas to pasture for beef production. Initially in AmazACRR and MaToPI the increase in productivity of cattle ranching would release area for soy production, but as the productivity effect accumulated, there was a change in the attractiveness (rate of return) of the agricultural activities, which begins to release area for beef cattle ranching.

Table 9. GHG emissions in the original accounting method. Percentage and Gg CO_2eq cumulative change in 2025, 2030, and 2035 from the baseline

Source		**Gg CO2eq**			**%**	
	2025	**2030**	**2035**	**2025**	**2030**	**2035**
Mining	-237	-711	-1236	-0.12	-0.34	-0.53
Other fuel	-438	-1091	-1785	-0.16	-0.37	-0.55
Gasoline C	318	662	946	0.36	0.65	0.82
Ethanol	57	126	191	0.34	0.65	0.88
Activity	42684	95184	154.023	5.33	10.80	16.39
LUC	-4692	-2533	-1303	-2.04	-1.05	-0.53
Total	37692	91636	150836	3.10	6.25	9.31

Source: authors results.

According to Villoria et al. (2014) (most evaluations of land productivity growth show avoided deforestation results (Borlaug effect). However, the authors mention that different results may occur depending on the geographic location and scope of the technological progress. For example, Villoria et al. (2013) (showed that increasing palm oil productivity in Indonesia and Malawi would increase deforestation in these countries, but would more strongly reduce deforestation in India, Canada, and Brazil, thus decreasing deforestation globally. This result is similar to what we found for the AmazACRR and MaToPI regions compared to the rest of Brazil.

Despite the GHG emissions mitigation from LUC, in the traditional GHG emissions accounting method[17] cattle production increases would imply 27.8% more emissions from beef cattle and 9.53% from dairy cattle. As cattle ranching represents 68.1% of GHG emissions from the activity level, the total national increase in GHG emissions would be 150,836 Gg CO2eq (9.31%) in 2035 (Table 9). As RPD increases the level of production of cattle ranching, there is an expansion of the herd, which in turn would emit greater volumes of GHGs. At the same time, RPD increases the demand for inputs for pasture recovery operations, such as fuel for machinery and agricultural implements, seeds, and pesticides, which would also contribute to increasing GHG emissions.

However, increasing land productivity can be associated with changes in GHG emission coefficients per unit of output (emission intensity) and SOC fixation, therefore in the alternative GHG emissions accounting method, mitigation from beef and dairy cattle would be 0.77% and 1.18%, respectively, which would provide a national total mitigation of 419 Gg CO_2eq (-0.16% total GHG emissions in relation to the baseline) in 2035 (Table 10). The results show that the SOC fixation can more than offset the implications of economic activity growth. Additionally, the change in emissions intensity is only partially captured by our simulation strategy, since aspects such as herd composition, diet digestibility, and other factors that impact GHG emissions from livestock according to the IPCC (2019), could not be incorporated into the model due to lack of data.

[17] see the alternative method results in Table 12

Table 10. GHG emissions in the alternative accounting method. Percentage and Gg CO2eq cumulative change in 2025, 2030, and 2035 from the baseline

Source	**Gg CO2eq**			**%**		
	2025	**2030**	**2035**	**2025**	**2030**	**2035**
Mining	-237	-711	-1236	-0.12	-0.34	-0.53
Other fuel	-438	-1091	-1785	-0.16	-0.37	-0.55
Gasoline C	318	662	946	0.36	0.65	0.82
Ethanol	57	126	191	0.34	0.65	0.88
Activity	**-255**	**-359**	**-419**	**-0.04**	**-0.05**	**-0.06**
LUC	-4692	-2533	-1303	-2.04	-1.05	-0.53
Total	**-5247**	**-3907**	**-3606**	**-0.04**	**-0.10**	**-0.16**

Source: authors results.

In the alternative method of accounting for GHG emissions, with the exception of AmazACRR and Rondônia, there would be an absolute reduction in the level of emissions from cattle ranching. The GHG emissions intensities of beef cattle ranching in RSul, AmazACRR, and MaToPi would reduce by more than 30% relative to the original method, highlighting the potential effect of SOC change both for consolidated regions such as RSul, and agricultural frontier regions such as AmazACRR and MaToPi (Table 11).

Table 11. GHG emission intensity and absolute volume by GHG accounting method. Percentage cumulative change in 2035 from the baseline

Regions	**Absolute volume**				**Emissions intensity (CO_2eq/production)**			
	Original		**Alternative**		**Original**		**Alternative**	
	Beef	**Dairy**	**Beef**	**Dairy**	**Beef**	**Dairy**	**Beef**	**Dairy**
Rondonia	35.06	14.49	0.01	-0.74	-0.27	-0.59	-26.16	-13.82
AmazACRR	48.85	19.97	0.55	-0.56	-0.18	-0.54	-32.57	-17.56
ParaAP	23.39	6.20	-0.06	-0.83	-0.22	-0.50	-19.18	-7.08
Bahia	18.80	9.09	-0.70	-1.44	-0.26	-0.48	-16.63	-10.09
MaToPi	43.02	21.27	-1.94	-4.56	-0.31	-0.59	-31.65	-21.77
RNordeste	13.29	1.44	-0.55	-0.88	-0.21	-0.37	-12.40	-2.66
MinasG	6.02	3.41	-0.89	-0.63	-0.23	-0.39	-6.73	-4.28
SaoPaulo	22.75	11.91	-0.29	-0.53	-0.27	-0.47	-18.99	-11.54
RSudeste	17.03	5.82	-1.01	-0.83	-0.24	-0.47	-15.62	-6.73
Parana	1.38	-5.99	-0.24	-0.60	-0.20	-0.34	-1.79	5.38
RSul	49.03	22.87	-2.61	-2.17	-0.34	-0.57	-34.87	-20.83
MtGrSul	14.96	3.84	-0.47	-2.87	-0.25	-0.51	-13.64	-6.94
MtGrosso	40.47	21.29	-0.60	-3.79	-0.32	-0.64	-29.47	-21.18
GoiasDF	33.14	20.17	-0.40	-0.78	-0.31	-0.55	-25.42	-17.89
Brazil	27.77	9.53	-0.77	-1.18	-0.09	-0.07	-22.41	-9.84

Source: authors results. Only accounted fuel and activity level GHG emissions. Original: original GHG emissions accounting method; Alternative: alternative GHG emissions accounting method.

FGV (2017) and Stocco et al. (2020) also found similar results regarding land use[18]. In the first phase of the ABC Plan (2010 to 2020), FGV (2017) showed that the RPD and livestock-crop-forestry integration would avoid deforestation of 4.85 to 5.09 Mha, resulting in mitigation of 50,100 GgCO_2eq. The previously mentioned analysis of Stocco et al. (2020) estimated 0.88 Mha of avoided deforestation, representing GHG mitigation of 8,176.5 GgCO_2eq, or -9.71% relative to the baseline.

[18] Ferreira Filho and Horridge (2016) analyzed compliance with targets regarding deforestation, so that RPD would not generate additionality on LUC. Authors such as Gurgel et al. (2019) and Machado et al. (2019) conditioned the results on NDC compliance, not allowing disaggregation of the impacts of RPD on deforestation. Souza et al. (2020) do not present GHG emissions or LUC data.

Econometric evaluations of cattle ranching intensification also showed land-saving behavior, Garrett et al. (2018) in a sample of Mato Grosso municipalities, presented that pasture intensification expanded the area of native vegetation in neighboring municipalities. Among the explanations for this result are the budget constraints of cattle ranchers to acquire and open new areas after investments in intensification, the low price-demand elasticity of meat, and speculative and value reserve aspects of cattle ranching, characteristics not necessarily related to the profitability of the activity.

Considering the original method of GHG emissions accounting, Brazil would meet the NDC mitigation target for 2025 (37%), but not for 2030 (50%), registering mitigation of 37.84% and 29.79%, respectively (Table 12). In the alternative method, mitigation levels would be higher in 2025 and 2030 (42.86% and 38.89% respectively), but still not enough to meet the 2030 target. SOC fixation alone would account for 13.6% and 18.4% of the GHG mitigations required for the 2025 and 2030 NDC targets when comparing the results of the original and alternative methods. The non-attainment of the 2030 target was also highlighted by Ferreira Filho & Horridge (2016, 2017)[19], however, the policy analyzed by the authors would result in a diminution of economic growth, differently from the present simulation.

Table 12. GHG emissions mitigation results versus NDC targets. Percentage change in 2025 and 2030 from the baseline

CEN 3	**2025**			**2030**		
	GHG	**HOU**	**GDP**	**GHG**	**HOU**	**GDP**
NDC target	37.00			50.00		
Baseline	38.94			32.91		
Original method	37.84	0.29	0.23	29.79	0.53	0.41
Alternative method	42.86	0.29	0.23	38.89	0.53	0.41

Source: authors results. GHG: GHG emissions; HOU: real household consumption; GDP: real GDP.

Conclusion

The RPD would generate economic growth in all Brazilian regions, associated with an environmental cost (increase in GHG emissions) if SOC fixation results are not incorporated into the GHG emissions inventory. This highlights the importance of establishing mechanisms for measuring and monitoring SOC change, especially in the RPD areas, enabling Brazil to better define subsidies and incentives for RPD in the national territory.

Livestock production intensification would result in greater growth in household consumption and GDP in the North, Midwest, and Matopiba regions, i.e., less developed regions, highlighting the distributive role of the RPD. Nevertheless, poorer families in Bahia, the Northeast, and Minas Gerais, would present a decrease in real consumption as a result of reduced demand for low-skilled labor in cattle ranching, which, unlike the other regions, would not be balanced by the economic activity increase. This result highlights the need for compensatory policies to accommodate the reallocation of the labor market from cattle ranching to other activities in less developed regions.

The RPD proved to be able to avoid deforestation for agricultural activities in Brazil, with the exception of the agricultural frontier regions (AmazACRR and MaToPi). This result shows the need for complementary policies in these locations to avoid deforestation leakage, which showed potential to reverse the LUC GHG emissions mitigation by its concentration in Amazon biome areas.

The policy impacts would not be enough, by itself, to meet the Brazilian NDC targets. However, RPD could contribute to 18.4% of the GHG mitigation required for the 2030 target, while providing a social rate of return of 16.04% per year. Despite the non-compliance with the NDC targets, it should be noted that these do not depend exclusively on the RPD or the agricultural sector so other actions should also contribute to the GHG emissions mitigation. Finally, the present research does not exhaust the GHG emissions intensity change from RPD due to the lack of information on the technological structure impacts in livestock production, such as herd

[19] The 2005 GHG emission level has been revised over time, so papers in the literature present different benchmarks than the current paper. Stocco et al. (2020) did not compare simulation results to NDC targets.

composition, digestibility of animal diets, and other aspects that influence the GHG emissions which can be addressed in future research.

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Appendix Table 1. Activities and products in the model

Activities/products	Description
Rice	Rice, wheat, and other grains
Corn	Corn
Cotton	Herbaceous cotton, and other crop fibers
Sugar cane	Sugar cane
Soybean	Soybean
Other annual crops	Other annual crops and services
Citrus	Citrus
Coffee	Coffee
Other permanent crops	Other permanent crops and services
Beef cattle	Cattle and other live animals
Dairy cattle	Milk from cows and other animals
Pork	Pork
Poultry	Poultry and eggs
Forestry	Forestry
Fishing	Fishing and aquaculture
Mining	Mineral coal, iron ore, and others
Slaughter	Beef, pork, poultry, and processed fish
Processes food	Pasteurized milk, dairy products, sugar, vegetable and animal oils, processed grains, and other food and beverages
Agroindustry (non-food)	Animal feed, tobacco, textiles, wood products, and others
Other manufactured	Paper, rubber, plastic, cement, and other products
Gasoline C	Gasoline C
Ethanol	Ethanol and other biofuels
Other fuel	Aviation fuels, Diesel, and other petroleum refinery products
Chemical	Inorganic and organic chemical products, fertilizers, paints, perfumery, pharmaceuticals, and other chemicals
Metallurgy	Steel, iron, and other metals products
Electrical and electronic	Electronic components, appliances and materials
Automobiles	Automobiles, tractors, aircrafts, and other transport equipment
Electricity and gas	Electricity, gas and other utilities
Water and waste	Water, sewage, recycling and waste management
Construction	Buildings and construction services
Trade	Trade
Transport	Transportation services
Hotel and food	Hotel and food services
Communication	Newspaper, telecommunications, and other services
Health and education	Health and education services
Public administration	Public administration
Domestic services	Domestic services
Other services	Services not listed above

Source: authors.