SUSTENTABILIDADE EM DEBATE

HOW WILL THE PRODUCTION OF AGRICULTURE COMMODITIES MEET BRAZIL'S CLIMATE TARGETS IN THE AMAZON AND CERRADO BIOMES?

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ABSTRACT

The Amazon and Cerrado regions are the main sources of agricultural commodities and greenhouse gas emissions (GHG) in Brazil, especially from cattle ranching and soybean. Production of both beef and soy is expected to increase in the country by 2030, with a possible impact on the Brazilian Nationally Determined Contribution (NDC) to the Paris Agreement. This study investigates the conditions for the Amazon and Cerrado regions to meet climate and production targets by 2030, according to two scenarios: 1) expanding pasture and soybean areas through legal conversion of native vegetation using business as usual (BAU) production management practices; 2) intensifying cattle ranching to spare pasture areas for soybean expansion without native vegetation conversion. Results show that management of the current soybean (20.9 million hectares - Mha) and pasture (106.1 Mha) areas in the Amazon and the Cerrado emitted 326.4 ±76.6 MtCO2e in 2015 - almost three quarters of GHG emissions from the Brazilian agriculture sector that year (490.9 MtCO2e). Approximately 56% of this GHG emission came from the Cerrado biome and 97.4% was related to beef cattle production. The only source of uncertainty accessed in this work was related to soil carbon stock variation. According to the Scenario 1, pasture and soybean areas will have to expand into 11.2 and 9.5 Mha (20.7 Mha) of native vegetation, respectively, to achieve the expected production levels by 2030. In this scenario, GHG emissions from the management of expanded soybean (30.4 Mha) and pasture (117.3 Mha) production areas in the Cerrado and Amazon regions tend to be higher than 2005 levels and move away from the NDC target for the agricultural sector (due increase in the cattle herd and use of production inputs), but not significantly due uncertainties in the soil carbon stocks variation. However, emissions from legal conversion of native vegetation to expand 20.7 Mha of production area would emit 2.7 GtCO2e until 2030. According to the Brazilian NDC, these emissions must be compensated in order to achieve the Land Use and Forest sector target. This level of offsetting is close to 125% of Brazil's GHG emissions (2.1 GtCO2e in 2015), thus the Scenario 1 leads to a significant burden for accomplishing the country's NDC. Under the Scenario 2, increasing cattle stocking rate by 8.5% above the BAU level (from 1.06 to 1.15 UA ha-1) should be enough not only to spare 9.5 Mha of pastures suitable for soybean expansion but also to meet beef expected production by 2030. GHG emissions from the land use and management of Scenario 2 tend to be lower than 2005 levels and closer to the NDC target for the agricultural sector (mainly due to the pasture area retraction and higher cattle production efficiency). In addition, large scale offsetting of GHG emissions is avoided under Scenario 2 once no conversion of native vegetation is needed to meet beef and soybean 2030 demands. However, implementing the second scenario requires improving policies aimed to couple pasture intensification with incentives to avoid legal conversion and to spare land for other production systems. Fostering moderate pasture intensification, adjusting and creating credit lines and mechanisms to stimulate forest conservation and land sparing as well as stablishing a robust monitoring system are fundamental steps to identify adequate low carbon agriculture models for achieving multiple environmental and productive benefits for and from the Cerrado and Amazon biomes.

INTRODUCTION

Brazil is one of the top 10 greenhouse gas (GHG) emitters in the world (WRI-CAIT, 2012). Close to 70% of Brazilian GHG emissions comes from land use change and agricultural activities, with the Amazon and Cerrado biomes as the main sources of these emissions, especially from pasture and soybean production (SEEG, 2018). Today, the Amazon and Cerrado regions have close to 20.9 million hectares (Mha) of soybean (3.7 and 17.2 Mha respectively), 106.1 Mha of pastures (43.0 and 63.1 Mha respectively) and 110.8 million animal units (AU) of cattle, which are potentially responsible for more than 60% of today's soybean and beef production in Brazil (Brandão Junior et al., 2017; Parente et al., 2017; ABIOVE, 2016).

Beef and soybean production in Brazil is expected to increase by 25% and 65% in the next decade, respectively (MAPA, 2017), and the Cerrado and Amazon regions are certainly target areas for meeting these expectations. These regions have almost 40 million hectares of native vegetation that could be cleared under full legal compliance with the forest code, of which 19 million hectares are suitable for soybean production and 84% are concentrated in the Cerrado (Brandão Junior et al., 2017). In addition, it is estimated that more than 50% of the total area of cultivated pastures in these regions are degraded (Costa and Rehman, 1999; Dias-Filho and Andrade, 2006) and could be used to increase beef production as well as to spare land for cropping expansion (Brandão Junior et al., 2017; Strassburg et al., 2014).

However, future agricultural production must keep GHG emissions no higher than 2005 levels. In addition, emissions from legal deforestation must be offset for the Brazilian Nationally Determined Contribution (NDC) to the Paris Agreement (Brazil, 2015) to be met. GHG emissions from agriculture production are correlated and affected by many variables, such as farm edaphoclimatic conditions, soil tillage, crop rotation, fertilizer and residue management, pasture intensification strategies as well as beef cattle production phases (e.g., breeding, rearing, fattening) (Raucci et al., 2015; Kappes, 2013; IPCC, 2006; Cardoso et al., 2016; Figueiredo et al., 2016; Piatto et al., 2016; Maia et al., 2009; Cerri et al., 2007). Therefore, changes in land use and agricultural practices for expanding beef and soybean production may significantly affect GHG emissions and will influence the success of Brazil's climate pledge.

Considering the importance of the Amazon and Cerrado regions to the production of agricultural commodities and to GHG emissions in Brazil, this study investigates the conditions for these regions to meet climate and beef and soybean production targets by 2030, according to two scenarios: 1) expanding pasture and soybean areas through legal conversion of native vegetation using business as usual (BAU) management production practices; and 2) intensifying cattle ranching and sparing suitable pasture areas to accommodate soybean expansion without further land conversion.

MATERIALS AND METHODS

Current and potential agricultural area in the Amazon and Cerrado regions

To determine the current and potential agricultural area in the Amazon and Cerrado regions we used results from Brandão Junior et al. (2018). This work estimates that there are currently close to 20.9 Mha of soybeans (3.7 and 17.2 Mha, respectively, in the Amazon and the Cerrado) and 106.1 Mha of pastures (43 and 63.1 Mha, respectively) in these regions. Of the already cleared area used for pasture today, 56 Mha are suitable for agriculture, including soybean production (27% and 73% in the Amazon and the Cerrado respectively) (Figure 1). Therefore, there is an additional net area of 3 Mha to be potentially opened without violating Forest Code restrictions (Soarez-Filho et al., 2014) in the Amazon (2 Mha suitable for pastures and 1 Mha for soybean) and almost 35 Mha in the Cerrado (15.96 Mha suitable for pastures and 18.83 Mha for soybean) (Figure 1).

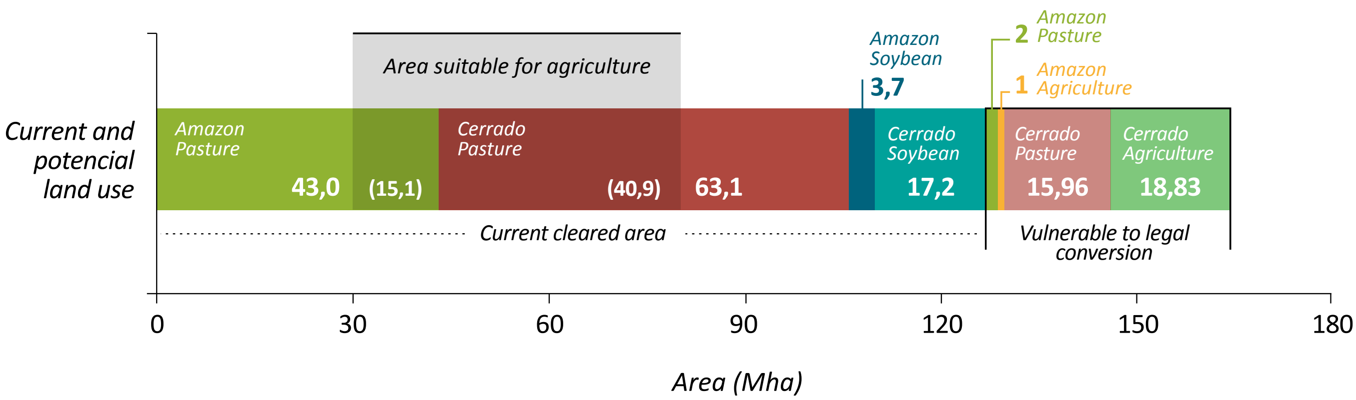


Figure 1. Current and potential land use for pasture and soybean under full legal compliance with the Brazilian Forest Code (Vulnerable for Legal Conversion) in the Cerrado and Amazon regions.

Future beef and soybean expected productions

Projections of expected beef and soybean productions by 2030 were obtained using historical (2000-2016) and projected (2017-2027) data for Brazil from the IBGE and the Brazilian Ministry of Agriculture (MAPA, 2017). Based on these data, we linearly extrapolated beef production and soybean area and production to 2030. We assumed that the share of Brazilian beef and soybean production from the Cerrado and Amazon regions is equivalent to the soybean area and cattle herd size in these regions. The pasture area and cattle herd necessary to meet 2030 beef expected production were estimated using historical data (2000–2016) on pasture area, cattle herd and beef productivity from IBGE, USDA-FAS, Cardoso et al. (2016) and Parente et al. (2017).

Future pathways for meeting climate and expected production targets

Land use and management scenarios

Brandão Junior et al. (2018) established 4 major scenarios for the land use in Amazon and Cerrado regions. These scenarios are further disagregated by production suitability (agriculture or livestock), which may also be farmed by different levels of management intensification. Therefore, the combination of land use, suitability and management intensification result in at least 16 possibilities for beef and soybean production scenarios over the Amazon and Cerrado.

The present study investigated only 2 of these possible scenarios to meet beef and soybean expected productions and their respective GHG emissions impact by 2030 - which are amongst the most current discussions in beef and soybean roundtables in Brazil:

1) Expanding pasture and soybean areas through legal conversion of native vegetation using business as usual (BAU) management production practices; and

2) Intensifying cattle ranching and sparing pasture areas suitable to accommodate soybean expansion without further native vegetation conversion.

GHG emissions and agricultural production factors

To estimate agricultural production (beef and soybean) and GHG emissions in the scenarios described above we developed factors based on national data bases (IBGE), IPCC guidelines (IPCC, 2006) and scientific literature (Cardoso et al., 2016; Raucci et al., 2015; Maia et al., 2009). For this work, GHG emission and production factors were considered for five pasture-based full-cycle beef cattle production systems (from 0.5 to 2.75 UA ha-1) for Brazil (Cardoso et al., 2016), coupled with soil carbon stock variation values for degraded and improved pastures in the Amazon (Maia et al., 2009). For soybean, we considered factors using two production strategies (single and double cropping systems) commonly found in the Amazon and Cerrado regions (Raucci et al., 2015; Kappes, 2013; Costa Junior et al., 2013; IPCC, 2006; Bayer et al., 2006) (Table A1).

It is worth noting that there are many uncertainties associated with the factors used in this work from activity data (i.e. level of pasture degradation, animal management, status of no-tillage adoption in soybean production, the use of soil inputs and the capacity of soils to sequester carbon) to emissions factors - in spite of most of them having a Tier 2 level of precision (IPCC, 2006; Table A.1). However, this work only assessed the role of uncertainty related to considering and not considering the soil carbon stock variation in the GHG estimates (Table A1).

Aboveground carbon stocks and GHG emission from land conversion

The amount of carbon stored in aboveground vegetation in areas vulnerable to legal conversion (Brandão Junior et al., 2017; Figure 1) was calculated using data from the Atlas Agropecuário (IMAFLORA, 2017; Freitas et al., 2018). GHG emissions from the conversion of this vulnerable vegetation into pasture and agricultural areas were calculated by multiplying the amount of aboveground carbon (Table 1) by 3.67 (conversion from carbon to carbon dioxide during total biomass combustion). Emissions of methane and nitrous oxide from land use conversion were neglected in this study.

BIOME	SUITABILITY	AREA (MHA)	TOTAL ABOVEGROUND CARBON STOCK IN VULNERABLE VEGETATION (t C)
Amazon	Pasture	2.0	252.4 ±57.2
	Agriculture	1.0	101.9 ±28.8
Cerrado	Pasture	15.96	352.7 ±183.5
	Agriculture	18.83	376.6 ±224.1
Total		**37.79**	**1,083.6 ± 296.6**

± represent uncertainties in parameters used in estimates.

Table 1. Area and total aboveground carbon stock of net vulnerable vegetation for legal conversion in the Cerrado and Amazon regions and its agricultural suitability.

RESULTS

Actual GHG emissions from beef and soybean production in the Cerrado and Amazon biomes

Emissions from the current management of soybean (20.9 Mha) and pasture (106.1 Mha) areas in the Amazon and Cerrado biomes were estimated at 326.4 ±76.6 MtCO2e in 2015. Approximately 56% of these emissions came from the Cerrado biome and 97.4% was related to beef cattle production (Figure 2). According to our analysis, each hectare of pasture and soybean in the Amazon and Cerrado regions emitted approximately 3.00 and 0.40 tCO2e y-1 and 48.2 and 0.12 tCO2e per ton of beef and soybean produced, respectively.

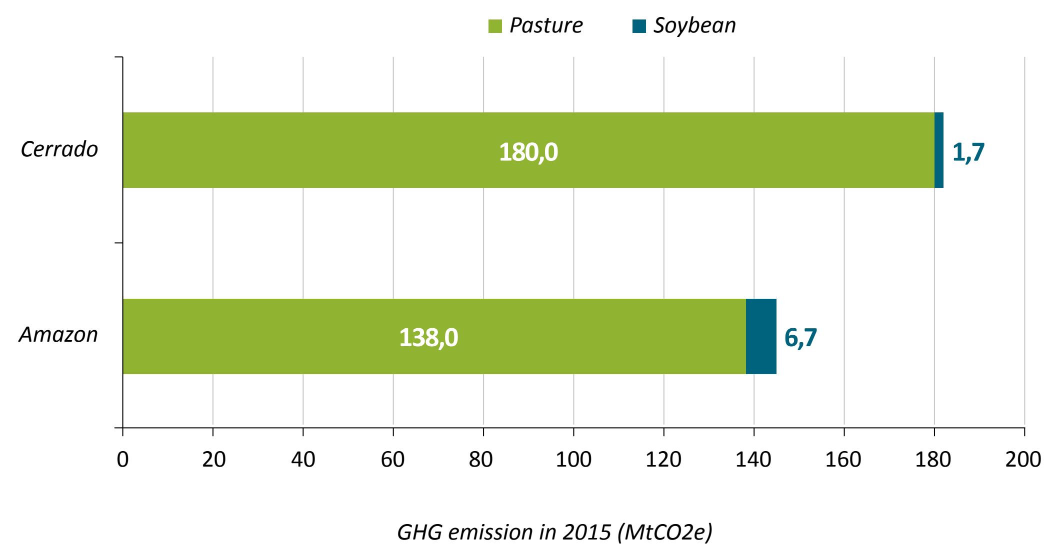


Figure 2. Estimated average greenhouse gas emissions from pasture (beef cattle) and soybean areas in the Amazon and Cerrado regions in 2015 (326.4 MtCO2e).

The level of GHG emissions from soybean and pasture management in 2015 (326.4 ±76.6 MtCO2e) accounts for to 67% of total emissions from the Brazilian agricultural sector that year (491 MtCO2e) (SEEG, 2018), with a trend towards a 5% increase in relation to 2005 levels (311.8 ±72.9 MtCO2e) (Figure 3), which is the Brazilian NDC reference year for the agricultural sector, with emissions from this sector in 2030 no higher than in 2005 (Brazil, 2015). These figures highlight the importance of soybean and beef production in the Amazon and Cerrado biomes to current and future GHG emissions in Brazil.

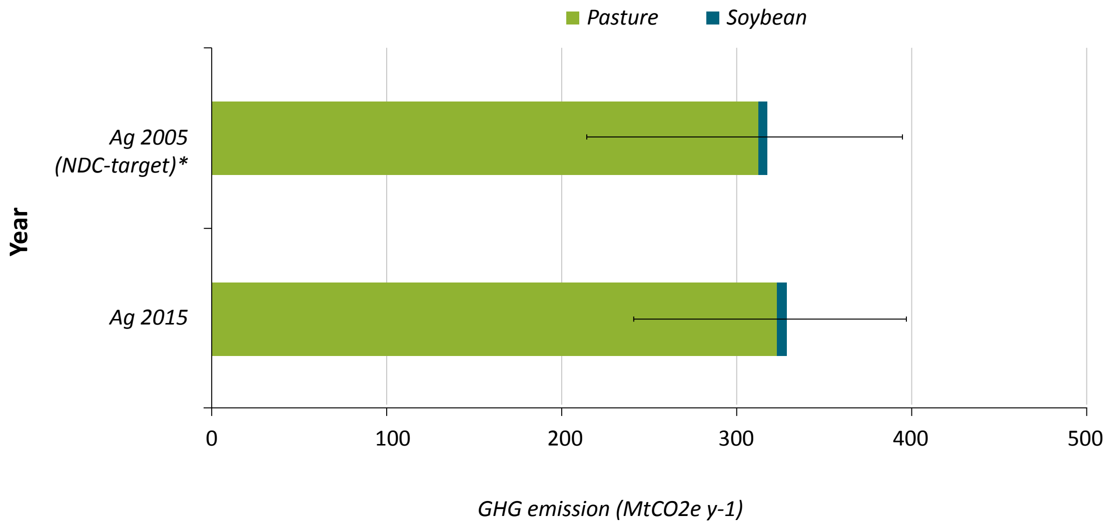


Figure 3. Estimated greenhouse gas emissions (GHG) from pasture (beef cattle) and soybean production areas in 2005 and 2015 in the Amazon and Cerrado regions. Bars represent uncertainties related to soil carbon stocks variation. *Assuming that the Brazilian NDC target for the agricultural sector (emissions in 2030 at 2005 levels) is applied to livestock and crop production, namely beef and soybean.

Given the complexity in modeling production of beef compared to soybean due higher and interrelated number of variables (pasture area, cattle herd, production and productivity), it is worth noting that the precision of the GHG emission factors for pasture (close to 98% of total emissions from agriculture management) used in this work is likely to be conservative, once calculated beef production underestimates modeled values (Figure A.2). Improvements in the estimate of beef production coming from the Amazon and Cerrado regions as well as beef production models that better represent these regions are also important steps to reduce uncertainties in GHG estimates of the present work.

Future production of beef and soybean

Based on historical data and government projections (IBGE; MAPA, 2017), meeting the 2030 expected soybean productions will require expanding 15 Mha of soybean cropping in Brazil, of which 9.5 Mha are expected to be in the Cerrado and Amazon regions (Figure 4; Table 2). Soybean production in Brazil increased close to 200% from 2000 to 2015 and is projected to grow another 70% from 2015 to 2030 (from 97.5 to 160.5 Mt). Nevertheless, an increase in soybean productivity of no more than 10% is expected over that same period (from 3.3 to 3.4 t ha-1). Therefore, expansion of the soybean area will probably occur in order to significantly increase its production by 2030.

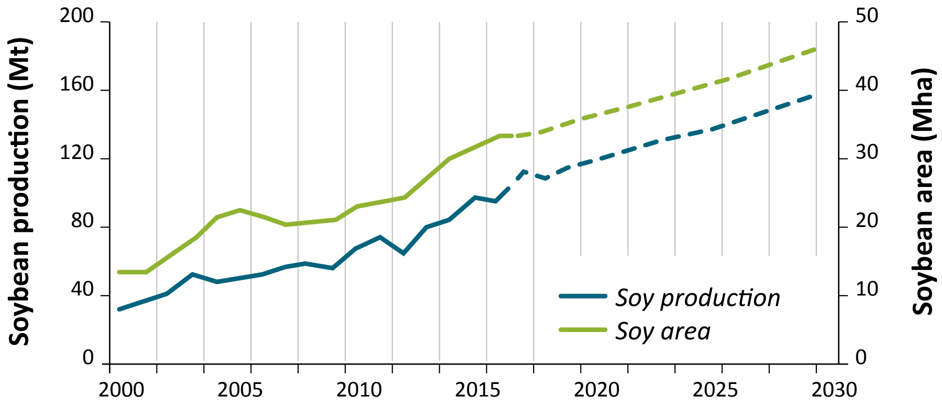


Figure 4. Historical and projected soybean production in Brazil by 2030

Beef production is expected to reach 12.1 Mt in 2030 under current trends (MAPA, 2017). Historically, from 2000 to 2015 the pasture area, cattle herd, beef production and beef productivity in Brazil increased 16% (from 152.0 to 176.0 AU), 27% (from 124.6 to 158.5 AU), 44% (from 6.5 to 9.4 Mt) and 24% (from 43 to 54 kg of beef ha-1y-1) respectively (Figure 5; Table 2). These numbers show that while productivity has improved over time, beef production in Brazil is still influenced by the increase in cattle herd and pasture area (Figure 5; Figure A1).

Therefore, in the BAU management scenario, meeting Brazil's beef expected production by 2030 (12.1 Mt) would require an extra 18.4 mi AU and 18.7 Mha of pasture lands, of which 14.0 mi AU and 11.2 Mha are expected to be in the Cerrado and Amazon regions (Figure 5; Table 2).

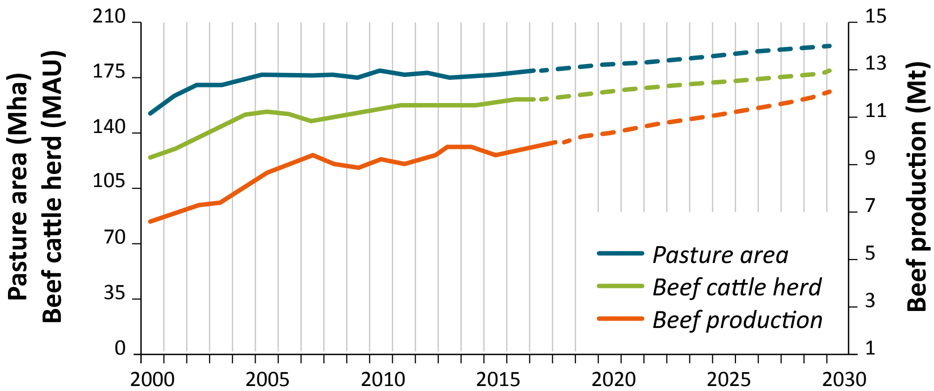


Figure 5. Historical and projected (under business as usual management) pasture area, cattle herd and beef production in Brazil by 2030

However, contrary to soybean, beef production can also be increased without expanding the pasture area and animal herd by improving its productivity. By adopting more efficient pasture and animal management practices, beef productivity may reach over 200 kg of beef ha-1y-1 or 4 times the current production rate (Figure A2; Cardoso et al., 2016). This last option can even allow pasture area retraction, thus sparing land for other uses, including the 9.5 Mha required for soybean expansion in the Cerrado and Amazon regions by 2030.

To be able to spare 9.5 Mha for soybean production without compromising beef production targets, the current pasture area and cattle herd size of the Amazon and Cerrado regions should increase from 1.04 to 1.15 AU ha-1, resulting in 96.7 Mha of pasture holding 110.8 M AU in these regions (Figure A2).

REGION	2015 (CurrentL)			2030 (EXTENSIFICATION)		
	Brazil	**Amazon**	**Cerrado**	**Brazil****	**Amazon‡**	**Cerrado‡**
Soy Area (M ha)	32.2	3.7 (11.5%)*	17.2 (53.4%)	46.9	5.4	25.0
Soy Production (M t)	97.5	10.3‡	48.5‡	160.5	17.0	79.8
Pasture Area (M ha)	176.0	43.0 (24.5%)	63.1 (36.0%)	193.8	47.5	69.8
Cattle Herd (M AU)	158.5	47.5 (29.9%)	63.3 (39.9%)	178.8	53.5	71.3
Cattle stocking (AUha-1)	0.90	1.10	1.00	0.92	1.13	1.02
Beef production (Mt)	9.4	2.8‡	3.8‡	12.1	3.6	4.8

*numbers in brackets represent the percentage of the total value (Brazil); **estimate based on projection by MAPA (2017), IBGE, Parente et al. (2017); Brandão et al. (2018); ‡estimated using the total value percentage. ‡assumed to be in the same proportion as in 2015.

Table 2. Estimated soybean and pasture area variables in 2015 and 2030 (under business as usual land use and management) in Brazil, the Cerrado and the Amazon.

Meeting future targets: Expanding beef and soybean production through legal conversion of native vegetation in the Amazon and Cerrado biomes

Under BAU management, the pasture and soybean area required to meet 2030 expected production (in Amazon and Cerrado regions) should be expanded by 11.2 and 9.5 Mha – reaching 117.3 and 30.4 Mha by that year, respectively. These expansions seem to be feasible considering that there are around 19 and 20 Mha, respectively, of native vegetation suitable for this production that could be legally cleared in the Amazon and Cerrado regions (Brandão Junior et al., 2017) (Figure 1; Table 1; 2).

GHG emissions from the expanded soybean (30.4 Mha) and pasture (117.3 Mha) area by 2030 are estimated at 367.5 ±86.8 MtCO2e (Figure 6). Almost 97% of these emissions would come from pastures for beef production (Figure 6; 7). This level of total emissions shows a tendency to be 18% higher than the NDC target for the Ag-Sector (311.8 ±72.9 MtCO2e) but should be enough for meeting the target considering uncertainties in estimates (Figure 6; 7).

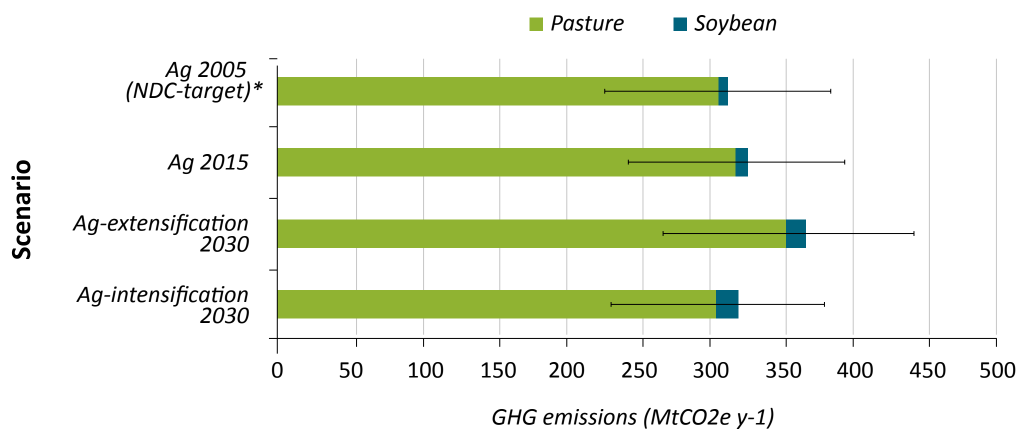
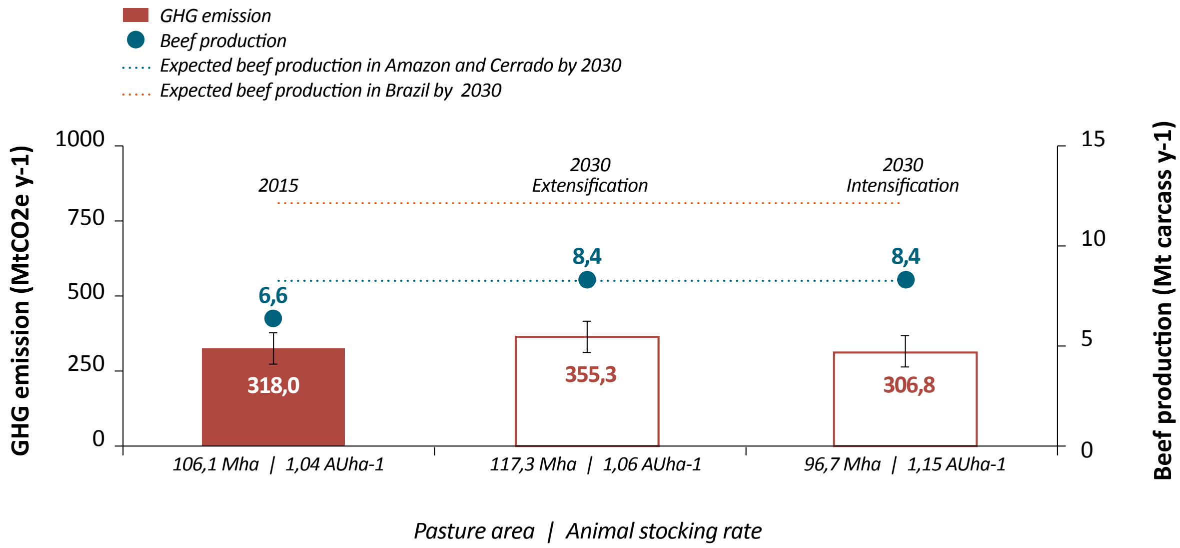


Figure 6. Estimated greenhouse gas emissions (GHG) from pasture (beef cattle) and soybean production areas in 2005, 2015 and two scenarios for production expansion by 2030 in the Amazon and Cerrado regions. Bars represent uncertainties related to soil carbon stocks variation. *Assuming that the Brazilian NDC target for the agricultural sector (emissions in 2030 at 2005 levels) is applied to livestock and crop production, namely beef and soybean.

In this scenario, average GHG emissions per hectare of pasture would be practically constant (from 3.00 to 3.03 tCOe2 ha-1 y-1). However, emissions from beef production would drop 12% (from 48.2 to 42.3 tCOe2 ton per beef produced) (Figure 7). BAU improvements in pasture and animal management may promote soil carbon sequestration and enhance beef production performance, which may potentially offset part of the emissions from the increased use of inputs (Table A1).

GHG emissions from soybean areas would not be affected (from 0.40 tCOe2 ha-1 y-1) and only a small emission reduction per ton of soybean produced is seen (from 0.120 to 0.117 tCOe2) (Figure 7). This is due to the increase in soybean productivity during this period (from 3.34 to 3.40 t ha-1 y-1 – MAPA, 2017).



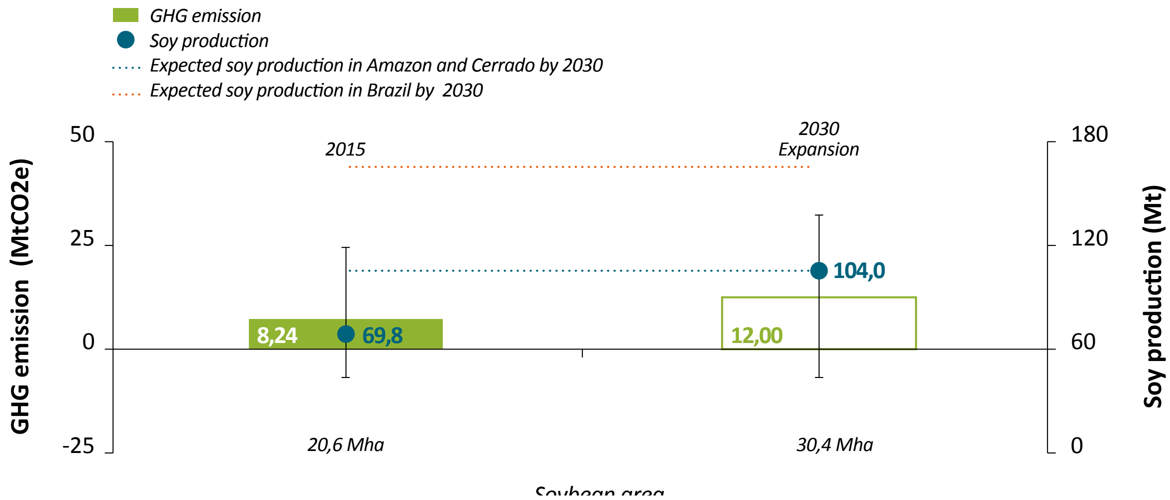


Figure 7. Estimated GHG emissions from the production of (A) beef cattle (under pasture extensification and intensification) and (B) soybean in 2015 and 2030 in the Amazon and Cerrado regions. Bars represent uncertainties related to soil carbon stocks variation.

On the other hand, this scenario requires offsetting GHG emissions from land use change (Figure 7). The expansion of 20.7 Mha of agriculture by 2030 (11.2 Mha of pastures and 9.5 Mha of soybean) would emit 2,670.4 ±1,075.1 MtCO2e due to losses of aboveground carbon during the conversion of native vegetation into pastures and soybean areas. We estimate that 63% of these emissions would come from the Cerrado biome (1672.5 ±598.2 MtCO2e) (Figure 8). This amount of GHG (2.7 GtCO2e) that would be emitted from legal deforestation is equivalent to around 125% of total Brazilian GHG emissions in 2015 (2.1 GtCO2e) (SEEG, 2018) or 14% of the amount of CO2 Brazil should emit in a worldwide effort to be likely to keep the global average temperature increase below 2 °C by 2050 (Rochedo et al., 2018).

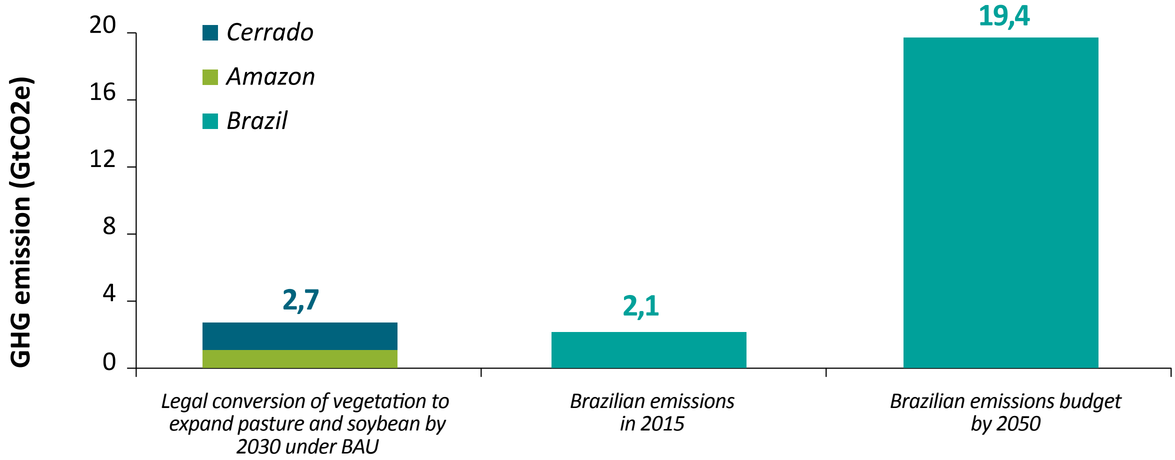


Figure 8. Greenhouse gas emissions (GHG) from legal conversion of the Amazon and Cerrado vegetation for expanding pasture (11.2 Mha) and soybean (9.5 Mha) areas to reach expected productions under Business as Usual Management (BAU) and Brazilian GHG emission in 2015 (SEEG, 2018) and 2017-2050 budget (all sectors) to meet worldwide effort to keep the global average temperature increase below 2 °C (Rochedo et al., 2018). Bars represent uncertainties related to above-ground carbon stocks.

Under the Brazilian NDC target for the Land Use and Forest sector, all emissions from legal conversion of native vegetation will need to be offset: "strengthening policies and measures with a view to achieving, in the Brazilian Amazon, zero illegal conversion by 2030 and offsetting greenhouse gas emissions from legal suppression of vegetation by 2030" (Brazil, 2015a). Although the NDC statement is directed more to the Amazon region, results of this work draw attention to large GHG emissions from land use change that may come from the Cerrado to support the expansion of agricultural commodities in the next years and which also need to be offset.

Thus, emissions from the management of expanded beef and soybean production areas in the Cerrado and Amazon regions should meet the NDC target for the agricultural sector by 2030. But emissions from legal conversions of native vegetation to expand pasture and soybean areas (2.7 GtCO2e) will have to be offset so that the NDC target for the Land Use and Forest sector can be met.

Meeting future targets: Increasing beef and soybean production through cattle ranching intensification and land sparing for cropping expansion

Another option for expanding beef and soybean production without increasing production areas and, consequently, avoiding large scale offsetting of GHG emissions from land use change is through the better use of consolidated agricultural areas, specially pastures. The Amazon and Cerrado regions have 106.1 Mha of pastures, of which 56.2 Mha are suitable for agriculture, including soybean production (Brandão Junior et al., 2017). If this area of 56.2 Mha is used for soy cropping, the current Amazon and Cerrado soybean production could be expanded by 300% or 6 times the production expected by 2030 (Figure 1; Table 2).

Sparing 9.5 Mha for soybean production expansion and meeting the beef production target (12.1 Mt) requires a pasture intensification from 1.04 to 1.15 AU ha-1 of the Amazon and Cerrado regions, resulting in 96.7 Mha of pasture holding 110.8 AU in these regions. This level of intensification is 8.5% above that expected from BAU animal stocking rate by 2030 (1.06 AU ha-1) (Table 2; Figure 7).

GHG emissions from intensified pastures (96.7 Mha) and expanded soybean area (30.4 Mha) in the Amazon and Cerrado regions would be 320.0 ±75.2 MtCO2e (96.2% from pastures - Figure 6; 7). This level of emission still has no significant difference compared to the NDC target for the Ag-sector (311.8 ±72.9 MtCO2e) and 2015 levels (326.4 ±76.6 MtCO2e) (Figure 7). However, it shows a tendency to be only 2% higher than the target and 13% lower than the extensification scenario (367.5 ±86.8 MtCO2e) (Figure 6).

Compared to 2015 levels, intensification of pasture areas showed a tendency (not significant) to increase emissions per hectare by 5% (from 3.00 to 3.17 tCOe2 ha-1 y-1), mainly due to higher use of soil inputs (Table A1), but emissions from beef production would be reduced by 24% from 48.2 to 36.5 tCOe2 ton per beef produced. GHG emissions from the soybean area would not be affected compared to the extensification scenario (Figure 6). However, the intensification scenario does not require offsetting GHG emissions from land use change (Figure 8; Brazil, 2015a).

Intensifying today´s beef production in the Cerrado and Amazon regions based on restoring degraded land and improving animal management (e.g., breeding techniques, rotational grazing and providing grain supplements), has the potential to increase by 4-5-fold the expected animal stocking rate (from 1.0 to 4.0 AU ha-1) and beef production (from ~80 to ~400 kg of carcass ha y-1) by 2030 (Bogaerts et al., 2017; Figueiredo et al., 2016; Cardoso et al., 2016; ICV, 2016). However, not all pasture management practices are able to potentially maintain the current levels of GHG emissions (Figure A2). For example, large scale beef cattle intensification over 2.0 AU ha-1 in 97.6 Mha could produce meat to supply more than 200% of the expected Brazilian production by 2030 (12.1 Mt). However, this would entail GHG emissions 2.5 times higher than today’s, not only compromising the agricultural sector’s ability to meet its NDC target (Brazil, 2015a) but potentially causing an oversupply of meat to the market (Figure A2).

POLICY RECOMMENDATIONS AND FINAL REMARKS

Using areas already cleared in the Amazon and Cerrado biomes seems to be a promising roadmap to meet expected production of beef and soy commodities under zero conversion of native vegetation while meeting Brazil's climate pledges. According to our analysis, maintaining the current herd size (110.8 M AU) and intensifying pastures by 8.5% in the BAU scenario (from 1.06 AU ha-1 to 1.15 AU ha-1) should be enough to spare 9.5 out of the 56.2 Mha of the pasture area suitable for soybean to meet both production (beef and soy) and climate targets (Brazil, 2015a) (Table 2; Figure 6; 7).

Without intensifying pasture lands and sparing area for soybean expansion, the production of both beef and soybean will probably have to be expanded into 20.7 Mha of native vegetation, possibly through legal pathways, to meet the expected productions by 2030. However, expanding the agricultural area into 20.7 Mha of native vegetation may lead to an emission of 2.7 ±1.1 GtCO2e that must be offset under the Brazilian NDC pledge (Figure 8; Brazil, 2015a). This emission budget is equivalent to 125% of total Brazilian GHG emissions in 2016 (SEEG, 2018) or 14% of the amount of CO2 Brazil should emit in a worldwide effort to be likely to keep the global average temperature increase below 2°C by 2050 (Rochedo et al., 2018) and, consequently, may add a significant burden on the country's ability to meet its NDC (Brazil, 2015a). In addition, GHG emissions from pasture and soy management tend to move away from their target.

Therefore, aligning Brazilian agriculture production and land use planning with the climate pledge is fundamental to avoid policy drawbacks. Together, the Amazon and Cerrado regions have close to 1,100 Mt C (3,976.9 ±1,811.7 MtCO2e) stored in vegetation vulnerable to being legally cleared (Table 1). This amount of carbon stocked could, for instance, be used to design programs and create incentives along with global supply chains and producers to foster improvements in agricultural management practices, such as pasture intensification and land sparing for other uses.

Pasture intensification is one of the most important issues on Brazil's climate and land use agenda. Together, the country's NAMA and NDC pledges, through the ABC Plan, aim to restore 30 Mha of degraded pasture from 2010 to 2030, in order to improve beef production, allow cropping expansion and reduce GHG emissions mainly through soil carbon sequestration (Brazil, 2015b).

These pledges seem to be timely and consistent, considering that pasture systems in the Amazon and Cerrado regions are characterized by a low animal stocking rate (~1 AU per hectare) and a high level of degradation (Fearnside and Barbosa, 1998; Costa and Rehman, 1999; Valentim and Andrade, 2009; Bustamante et al., 2012). It is estimated that more than 50% of the total area of cultivated pastures in the Cerrado biome (Costa and Rehman, 1999) and more than 60% in the Amazon biome (Dias-Filho and Andrade, 2006) are degraded and use less than 30% of their production capacity (Strassburg et al., 2014).

While beef productivity increased by 66% over the same period (2000-2015), it could be at least twice as high if well-known pasture and animal management techniques were deployed countrywide (Cardoso et al., 2016; Barbosa et al., 2015). This result suggests that both the pasture area and animal herd are somehow oversized for beef production and could probably be reduced without compromising expected production (Figure 6).

From 2000 to 2015 soybean productivity increased 26% (from 2.4 to 3.0 ton ha-1) but is expected to increase less than 10% from 2015 to 2030 (from 3.34 to 3.40 t ha-1) (MAPA, 2017; IBGE). Without investments in new technologies it seems that little can be done in the short term to significantly improve soybean productivity in Brazil compared to the potential increase in beef proportion. Thus, sparing pasture land to expand other cropping systems appears to be reasonable for supporting the expansion of both beef and soy production.

Since 2010, the ABC Program (credit line to reach ABC Plan goals) has disbursed more than ~3 bi USD (22 bi BRL) for low carbon agriculture practices (Observatório do ABC, 2017; Imaflora, 2018). Most of these resources have been invested in recovering pastures, but the lack of mechanisms to track the outcomes on the ground is a barrier to understanding the GHG mitigation effect and tradeoffs, such as intensification and land sparing – when demand for land expansion is reversed by increasing efficiency and production diversification of already opened areas. Thus, establishing such a mechanism may be a priority for the ABC Program to effectively finance low carbon agriculture practices without promoting emission leakage (such as from land use change) and, ultimately, to incentivize a better use of government resources (Merry & Soares-Filho, 2017). In addition, the ABC Program seems to be a good credit line to test innovative mechanisms of payment for the use of best management practices, land sparing and forest conservation within private areas.

Finally, reducing uncertainties in regional spatial information on pasture degradation levels, soil carbon storage capacity and suitability for intensifying beef production to spare land for adopting cropping systems in both the Cerrado and Amazon biomes are fundamental steps to better validate and understand the tradeoffs between GHG emissions balance, beef cattle intensification and land sparing; and, ultimately, to identify appropriate low carbon agriculture models for achieving multiple environmental and production benefits in these regions.

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ANNEX

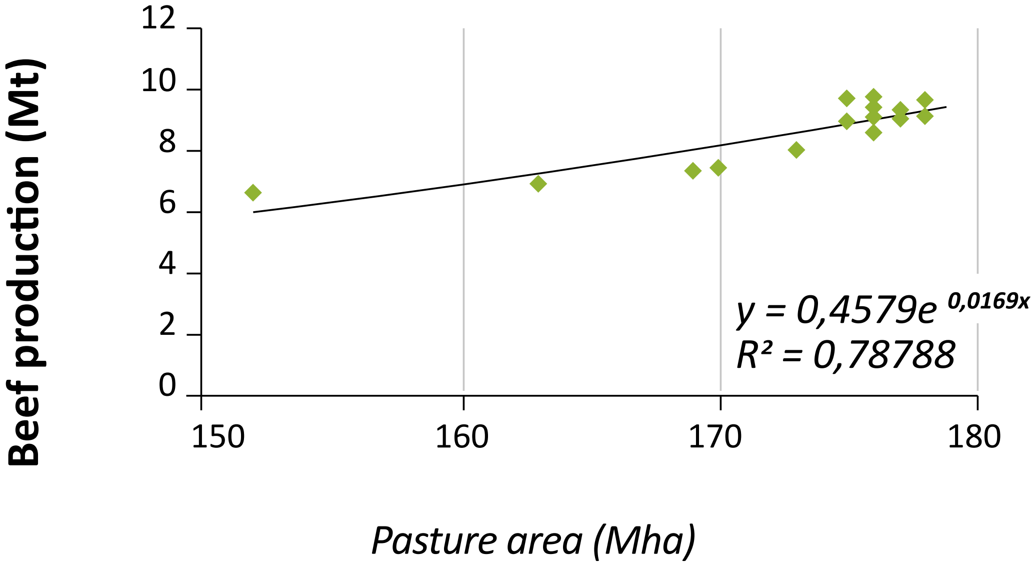
Table A1. Greenhouse gas emission (GHG) factors for soybean and beef production systems.

Production System	Condition	Management scenario	GHG emission tCO2e ha-1 y-1	GHG emission factor tCO2e ha-1 y-1
Soybean	Single Cropping	Single soy cropping under conventional tillage (soil plowing); diesel consumption of 36 l ha-1 -y; lime application averaging 489 kg ha-1 y-1 and N fertilizer (urea) at a rate of 8 kg N ha-1y-1 (Raucci et al., 2015). Soy production: 3.4 t ha-1; Soil carbon stock variation was considered to range from 0 (no variation) to -0.40 tCha-1 y-1 (soil C loss) (Corbeels et al., 2006; Costa Junior et al., 2013).	0.4 – 1.8	1.1 ±0.7
	Double cropping	Soy double-cropped with maize under no-tillage practice; diesel consumption of 72 l ha-1 -y; lime application averaging 489 kg ha-1 y-1 and N fertilizer (urea) at a rate of 68 kg N ha-1y-1 (8kg for soy and 60 kg for maize) (Raucci et al., 2015; Kappes, 2013). Soy production: 3.4 t ha-1; Soil carbon stock variation considered to range from 0 to +0.50 t C ha-1 y-1 (soil C sequestration) (Corbeels et al., 2006; Cerri et al., 2007; Bayer et al., 2006).	-1.2 – 0.6	-0.3 ±0.9
Pasture - Beef Cattle	Extensive	Animal stocking rate: 0.5 AU/ha; Pasture: Brachiaria sp.; Pasture Management: no pasture reform / no lime or fertilizers added; Breed of bovine: undefined – crossbreeds of Bos indicus and some blood of Bos Taurus; Effect of breed: First calving late High mortality. Animal slaughtered between 3 and 4 years/meat low quality; Diet in calving, rearing and finishing phases: Pasture forage only; Animal management: minimal, random animal; breeding and only compulsory vaccines; Low intensive machinery and electricity use; Beef production: 31.2 kg carcass per ha; GHG emissions of 2.0 tCO2e ha-1 y-1 (based on IPCC, 2013; details in Cardoso et al., 2016). Soil carbon stock variation was considered to range from 0 (no variation) to -0.28 tCha-1 y-1 (soil C loss) (Maia et al., 2009).	2.0 – 3.1	2.5 ±0.5

Pasture - Beef Cattle	Intensification 1	Animal stocking rate: 1.0 AU/ha; Pasture: B. brizantha; Pasture management: pasture reformed every 10 years. Lime (10 Mg/ha) every 10 year.; Breed of bovine: Mixed breed Nellore with Gir, Guzera, Holsteins, Curraleiro, and other Bos Taurus.; Breed effect: Standard Nellore characteristics. First calving at 3 years; Diet in calving, rearing and finishing phases: pasture forage with occasional mineral supplements; Animal management: Basic, with random animal breeding, only compulsory vaccines; Medium intensity of machinery and electricity use; Beef production: 74.7 kg carcass per ha; GHG emissions of 3.4 tCO2e ha-1 y-1 (based on IPCC, 2013; details in Cardoso et al., 2016). Soil carbon stock variation was considered to range from -0.28 (soil C loss) to +0.61 tCha-1 y-1 (soil C sequestration) (Maia et al., 2009).	2.2 – 3.4	2.8 ±0.6
	Intensification 2	Animal stocking rate: 1.7 AU/ha; Pasture: Mixed grass legume; Pasture management: pasture reformed every 5 years / lime (10 Mg) every 5 years / fertilized NPK.; Breed of bovine: Nellore or Nellore crossbreeds / predominantly blood of Nellore; Breed effect: first calving 2 year, more calves per cow, less mortality, animal finished early and higher carcass yield; Diet in calving phase: pasture forage with mineral supplements; Diet in rearing phase: pasture forage with mineral supplements; Diet in finishing phase: Pasture forage with mineral and energetic supplements; Animal management: breeding season, controlled weaning, control of endo and ectoparasites. Medium intensity of machinery and electricity use; GHG emissions of 4.5 tCO2e ha-1 y-1 (based on IPCC, 2013; details in Cardoso et al., 2016). Beef production: 140.2 kg carcass per ha (Cardoso et al., 2016). Soil carbon stock variation was considered to range from 0 (no variation) to +0.61 tCha-1 y-1 (soil C sequestration) (Maia et al., 2009).	2.3 – 4.5	3.4 ±1.1

Pasture - Beef Cattle	Intensification 3	Animal stocking rate: 2.5 AU/ha; Pasture: Guinea grass; Pasture management: pasture reformed every 5 years / lime (10 Mg) every 5 years / fertilized NPK.; Breed of bovine: Nellore or Nellore crosses- Best Nellore crosses; Breed effect: first calving 2 year, more calves per cow, less mortality, animal finished early and higher carcass yield; Diet in calving phase: pasture forage with mineral supplements; Diet in rearing phase: rotational grazing / pasture forage with mineral supplements; Diet in finishing phase: Rotational grazing. Pasture forage with mineral, protein and energetic supplements; Animal management: breeding season, controlled weaning, control of endo and ectoparasites. Intensive machinery and electricity use; GHG emissions of 6.9 tCO2e ha-1 y-1 (based on IPCC, 2013; details in Cardoso et al., 2016).Beef production: 201.7 kg carcass per ha (Cardoso et al., 2016). Soil carbon stock variation was considered to range from 0 (no variation) to +0.61 tCha-1 y-1 (soil C sequestration) (Maia et al., 2009).	4.6 – 6.9	5.8 ±1.1
	Intensification 4	Animal stocking rate: 2.75 AU/ha; Pasture: Guinea grass; Pasture management: pasture reformed every 5 years / lime (10 Mg) every 5 years / fertilized NPK.; Breed of bovine: Nellore or Nellore crosses- Best Nellore crosses; Breed effect: first calving 2 year, more calves per cow, less mortality, animal finished early and higher carcass yield; Diet in calving phase: pasture forage with mineral supplements; Diet in rearing phase: rotational grazing / pasture forage with mineral supplements; Diet in finishing phase: confinement with total mixed ration; Animal management: breeding season, controlled weaning, control of endo and ectoparasites. Intensive machinery and electricity use; GHG emissions of 6.8 tCO2e ha-1 y-1 (based on IPCC, 2013; details in Cardoso et al., 2016). Beef production: 221.4 kg carcass per ha (Cardoso et al., 2016). Soil carbon stock variation was considered to range from 0 (no variation) to +0.61 tCha-1 y-1 (soil C sequestration) (Maia et al., 2009).	4.6 – 6.8	5.7 ±1.1

Figure A1. Beef cattle production, cattle herd and pasture area correlations in Brazil using 2000-2016 data.



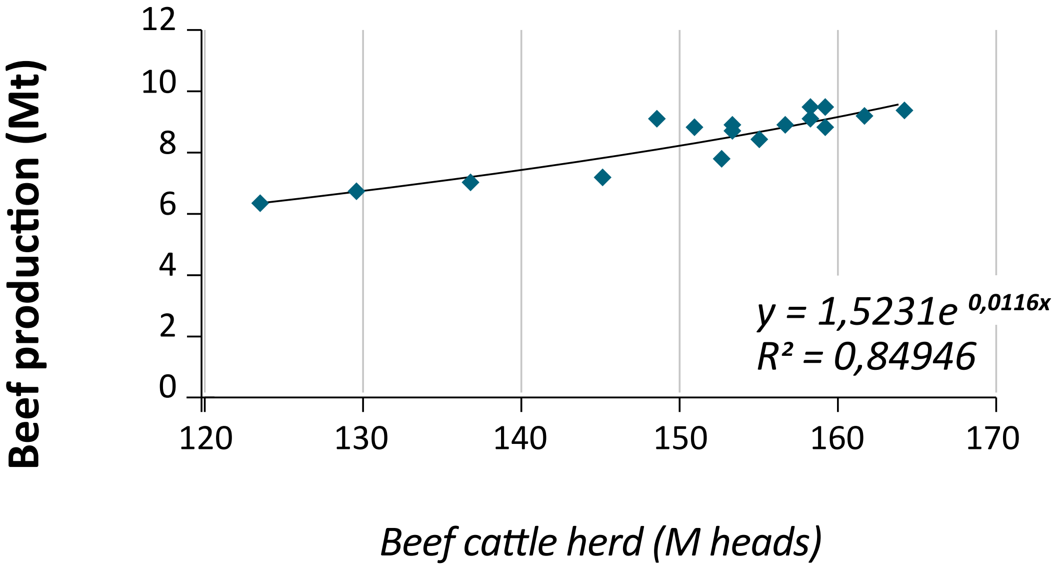
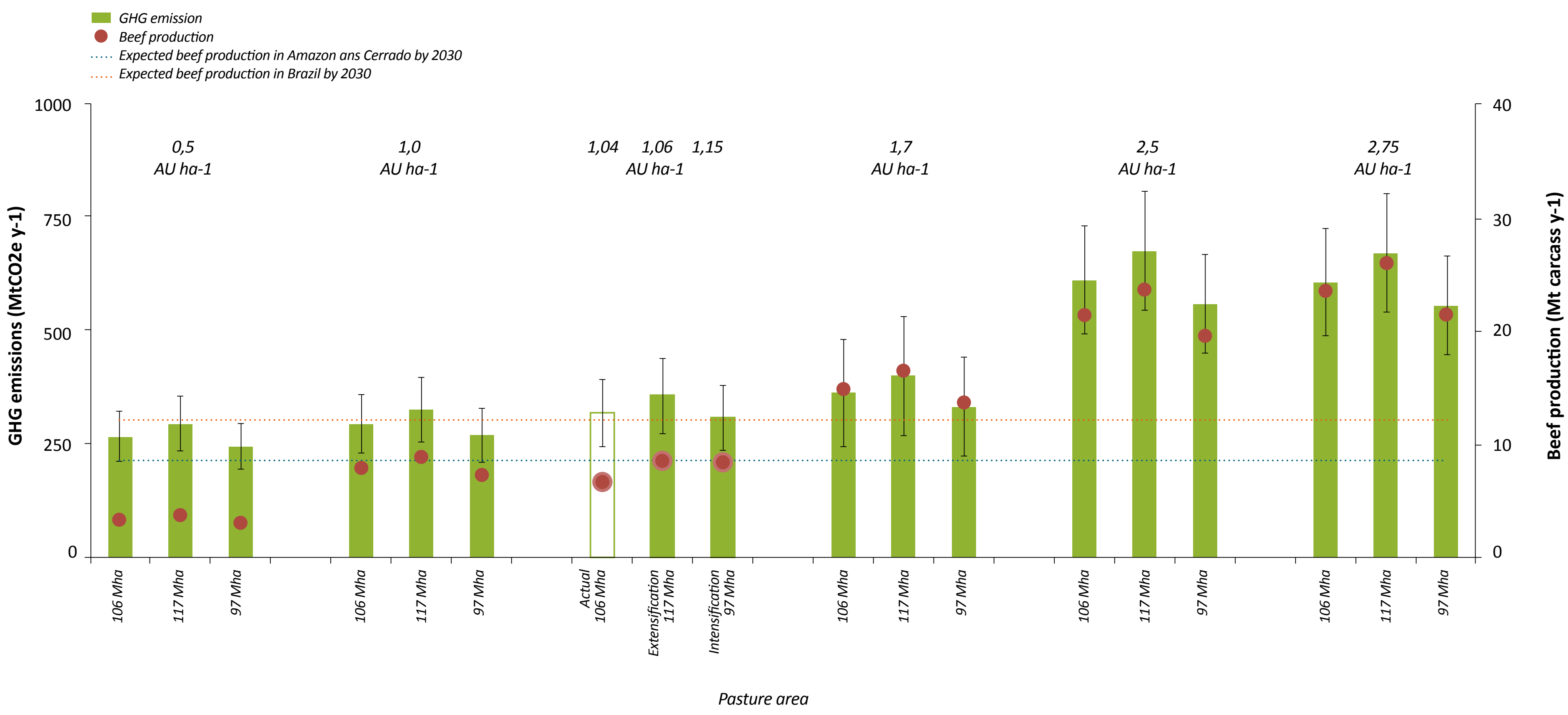


Figure A2. Beef cattle production validation. Note that there are still differences between beef production calculated in this work (Actual – 106 Mha / 1.04 AU ha-1) and the values provided by Cardoso et al. (2016) (see 106 Mha / 1 AU ha-1). These differences should be addressed in future works in order to reduce uncertainties in estimates.



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