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The role of agricultural intensification in Brazil’s Nationally Determined Contribution on emissions mitigation

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Abstract

Brazil is the first developing country to provide an absolute emissions cut as its Nationally Determined Contribution (NDC), seeking to reduce greenhouse gas (GHG) emissions by 37% below 2005 levels by 2025 and 43% by 2030. The NDC is also noteworthy in focussing on emissions from deforestation control and land use change. Agricultural intensification is a key component of the offer, potentially allowing the country to make credible mitigation commitments that are aligned with a national development strategy of halting deforestation in the Amazon, and increasing livestock production. This apparent contradiction is potentially resolved by understanding the technical, economic and policy feasibility of intensification by pasture restoration. We use bio-economic modelling to demonstrate the extent of cost-effective mitigation that could be delivered by this measure, and to show a result that underpins the target of zero deforestation in Brazil. The analysis was requested by the Brazilian Ministry of Agriculture prior to the NDC announcement at COP21 by the Government of Brazil. The study provided the basis of the livestock sector contribution to the NDC and highlights the on-going role of effective deforestation control policies. It also contributes to the global debate on land sparing by sustainable agricultural intensification.

Keywords: Agriculture; mitigation, sustainable intensification; deforestation; Amazon; *Cerrado*

Highlights

- The analysis was requested by the Brazilian Ministry of Agriculture and targets land sparing via cattle intensification.

- This work derives the livestock contribution (pasture restoration area) to the NDC deforestation target.
- Deforestation target dependent on restoration area of 16.2-18.2 Mha of degraded pasture.
- Under NDC 1.4 Gt of CO_2e emitted by 2030 due to pasture expansion could be reduced by 85%.

1. Introduction

National mitigation actions

Brazil’s Nationally Determined Contribution (NDC), offered at COP21 (Brazil, 2015), is the first time a major developing country has committed to an absolute reduction of emissions from a base year (2005), as opposed to reductions in projected emissions or per unit of Gross Domestic Product. The commitment for the 2020-30 period extends previous Nationally Appropriate Mitigation Actions (NAMA) that committed to an emissions reduction of 36.1% - 38.9% relative to baseline projections by 2020 (Brazil, 2010a). Table 1 summarises the land use change and livestock sector contribution to the NAMA and NDC.

Table 1: Land use change and livestock sector contributions to Brazil's National mitigation actions.

National mitigation action	Deforestation target	Livestock contribution	Action period	Offered at
NAMA	Reduction of 80% and 40%, respectively in the Amazon and *Cerrado* by 2020, in relation to average rates from 1996 to 2005.	Restoration of degraded pastures	2010-2020	COP15
NDC	Zero deforestation in the Amazon biome by 2030*.	Restoration of degraded pastures	2020-2030	COP21

*Although the NDC explicitly targets zero deforestation in the Amazon, this analysis assumed zero deforestation in all biomes.

Brazil's NAMA was notable for focussing on the largest emissions sources of forestry and land use change, establishing targets for the reduction of deforestation by 80% in the Amazon biome by 2020 (in relation to the average rate over 1996-2005), and by 40% in the *Cerrado* (Brazilian savannah - Fig. 1) (in comparison with the average deforestation rate 1999-2008); made technically feasible through the adoption of pasture restoration, and integrated crop–livestock–forestry systems (Mozzer, 2011). These measures aim to reduce emissions directly by increasing soil organic carbon stocks (SOC), and indirectly through land sparing, hence avoided deforestation.

The NDC poses a challenge to reconcile emissions reduction, deforestation and biodiversity conservation, with ambitious goals for livestock production, predicted to grow by 18% over the decade 2014-24 (OECD, 2016).

The policy intervention supporting the livestock contribution to the NAMA and NDC is in terms of a government-funded bank credit line for low carbon agriculture, the *Agricultura de Baixo Carbono* (ABC) - Low Carbon Agriculture program (Mozzer, 2011). The ABC program offers low interest credit lines to farmers adopting mitigation technologies, including pasture restoration.

In essence, the country is betting on large-scale sustainable agricultural intensification (SAI) (de Oliveira Silva *et al.*, 2016) of its key production systems, a challenge for agricultural science, technology adoption, and effectiveness of complementary deforestation policies. This paper evaluates the feasibility of this intensification challenge using scenarios tested in a bio-economic optimization model parameterized for the *Cerrado*, Amazon and Atlantic Forest biomes, which account for around 37%, 28.5% and 23.5% of national beef production respectively (IBGE, 2015). The objectives were to derive the livestock sector contribution to the NDC in terms of the degraded pasture area that could potentially be restored cost-effectively (henceforth restoration area), over the period 2020-2030 assuming accomplishment of the target for reduced deforestation (Table 1) and to estimate the demand for the ABC program. The analysis was requested by the Brazilian Ministry of Agriculture through the Brazilian Agricultural Research Corporation (Embrapa) prior to the NDC announcement at COP21 and offers a transparent and robust framework that supported the formulation of the Brazilian NDC, by demonstrating how the livestock contribution was derived.

The paper is structured as follows. The next section provides background on the historical trends linking agricultural production, deforestation and emissions, setting the scene for the role of SAI measures. Section three outlines the relevant data and modelling to represent pasture restoration as a key SAI measure. Section four provides modelling results, discussion and conclusions are presented in sections five and six respectively.

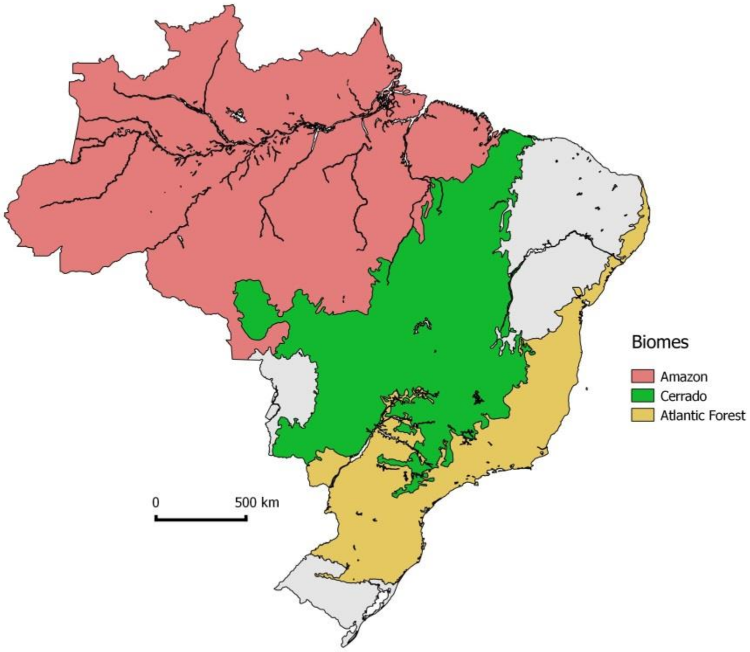


Figure 1: Brazilian main beef cattle biomes.

2 Agricultural development, deforestation and emissions

Brazil’s international environmental profile is significant in terms of the supply of global public goods associated with tropical forest conservation, including significant carbon sequestration and biodiversity (Nepstad *et al.*, 2014a). Brazilian beef production accounts for 15.5% of global production (FAO, 2015), most for domestic consumption. Exports have long been competitive, mainly because predominantly pasture grazed animals are less costly than feedlot systems used in competitor countries (Pedreira *et al.*, 2015). Historically (1950-1975), pasture expansion and extensive ranching explained around 86% of growth in production

(Martha *et al.*, 2012). These ranching systems were typically characterised by limited mechanization and low input use, e.g. fertiliser or seeds. Growth was also supported by government research and development programs focussed on the expansion and establishment of agriculture in frontier regions of the *Cerrado* and parts of the Amazon (Martha *et al.*, 2012). Ranchers also cleared forests to secure properties rights (Mueller, 1997).

Development of the *Cerrado* was a steep-change accelerating Brazil's global market ascendance (The Economist, 2010; Rada, 2013). From 1975 the productive potential of the region became clearer as producers reaped benefits from research on improved animal performance, and used better-adapted *Brachiaria* grasses (Martha *et al.*, 2012). This initial intensification era was partly at the expense of significant uncontrolled deforestation. Despite this step-change, average stocking rates nationwide remain low, around 1 head per hectare ($hd.ha^{-1}$) compared to a potential carrying capacity exceeding 2 heads per hectare ($hd.ha^{-1}$) (Strassburg *et al.*, 2014). This is partially explained by pasture degradation; grasses presenting low dry matter productivity insufficient for animal nutritional requirements.

The story of initial extensive and subsequent progressive agricultural intensification is one of multiple explanatory causes of observed and documented deforestation trends (Nepstad *et al.*, 2014b; Dias *et al.*, 2016). Peaking in 2004, annual deforestation rates have since followed a decreasing trend and are currently around 60% lower than the 1995-2005 average (INPE, 2017). FAO data show that pasture area decreased from 214 million hectares (Mha) to 196 Mha over the period 1995-2006, while cattle numbers continued to increase (FAO, 2015). Correspondingly, national emission inventory data (Brazil, 2014) show that while deforestation accounted for 57% of the 2.0 Giga tonnes of CO_2 equivalent (Gt CO_2e) emitted in 2005, this decreased to 15% of the 1.2 Gt CO_2e total emitted in 2012, which is partly explained by effective deforestation control policy (Soares-Filho *et al.*, 2010; Macedo *et al.*, 2012; Arima *et al.*, 2014; Lapola *et al.*, 2014). This means that Brazil has already significantly reduced emissions from deforestation (-82% from 2004 levels in 2014), while those from agriculture and the energy sector continue to grow (+7.4% and +35.9 respectively 2005-12), both sectors overtaking deforestation as the largest sources of emissions (Brazil, 2014).

The apparent decoupling of livestock output and deforestation, and scope for further pasture restoration, provides the basis for an NDC that is potentially consistent with accommodating an upward trend in livestock production to meet increasing demand. In essence Brazil's NDC can be interpreted as a version of SAI, a concept advanced to address the 'perfect storm' of climate change, population growth and food insecurity. SAI is contested and may include consumption, equity and justice dimensions (Loos *et al.*, 2014; Rockström *et al.*, 2016), but to date there have been few models demonstrating trade-offs that emerge when managing a globally significant production system.

3. Material and methods

3.1 Pasture and demand projections

The analysis covers the period 1996-2030, and is divided into historical pasture estimates 1996-2014 for the Amazon and 1996-2010 for the *Cerrado* and Atlantic Forest; and projections for the 2015-2030 and 2011-2030 periods, respectively for the Amazon and the *Cerrado* and Atlantic Forest (Fig. 2). There are no published historical data for annual pasture areas for Brazilian biomes. We therefore estimate biome-specific pasture area by aggregation from state level data as follows: initial pasture area was based on the publicly available IBGE 1996

Agricultural Census for each Brazilian municipality (≈5500) from the SIDRA database (https://sidra.ibge.gov.br/Acervo#/S/PA/A/Q). Pasture area was first aggregated at the state level and then proportionally allocated to each biome using equation Equation 1.

$$P_{b,t} = \sum_{s} P_{s,t} \frac{A_{s \cap b}}{A_s} \quad t = 1996 \quad (1)$$

$P_{b,t}$ is the pasture area of biome b in year t; $P_{s,t}$ is the pasture area of state s in year t; $\frac{A_{s \cap b}}{A_s}$ is the proportion of area of state s (A_s) covered by biome b ($A_{s \cap b}$).

For the consecutive years, historical annual pasture area is given by:

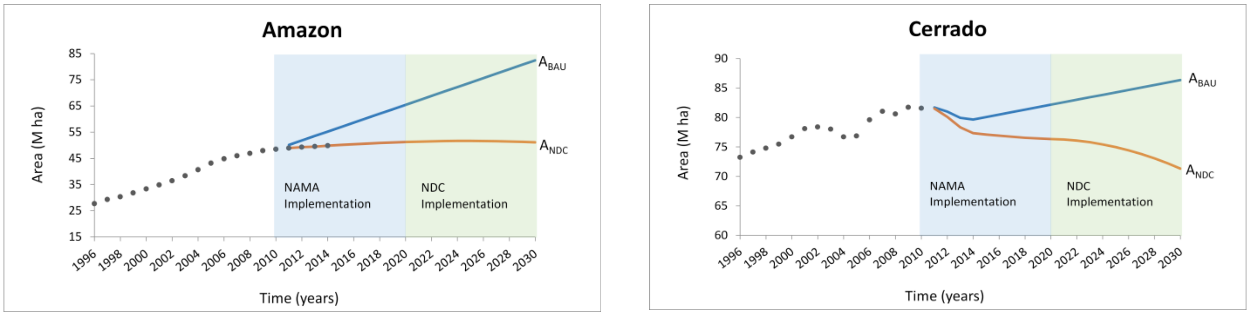
$$P_{b,t} = P_{b,t-1} - \Delta N_{b,t-1} - \Delta C_{b,t-1} - \Delta F_{b,t-1} \quad 1996 < t < 2014 \quad (2)$$

Where $P_{b,t-1}$ is the pasture area in the previous year $t-1$; $\Delta N_{b,t-1}$ is the variation of natural vegetation cover in the previous year; $\Delta C_{b,t-1}$ is the variation of cultivated area with permanent and annual crops and forestry; $\Delta F_{b,t-1}$ is the variation of area due to secondary forest growth and other uses (e.g., roads, urban expansion); $\Delta N_{b,t}$ was observed from 1996-2014 for the Amazon, 1996-2010 for the other biomes; $\Delta C_{b,t}$ data was available until 2014 (IBGE); $\Delta F_{b,t}$ was estimated by calibration against the variation of pasture area between the 1996 and 2006 agricultural censuses.

Equation (2) was also used for pasture area projections (2015-2030). The baseline projection (A_{BAU}) applied the observed period average of $\Delta N_{b,t}$ and $\Delta N_{b,t}$ to project pasture areas for 2015-2030. Projected $\Delta C_{b,t}$ was based on Gouvello et al. (2011). For the **NAMAs + NDC** (A_{NDC}), $\Delta N_{b,t}$ was computed so that the target levels of deforestation for each of the biomes in 2020 and 2030 are met. To produce trajectories with annual time steps, the targets were linearly interpolated.

The 2010-2020 period was interpolated having the observed $\Delta N_{b,t=2010}$ as the starting point and target $\Delta N_{b,t=2020}$ as the endpoint. For the 2020-2030 period, target levels for 2020 (NAMAs) and 2030 (NDCs) were interpolated. Since pasture area in the Atlantic Forest has been stabilized at least since 2001 (http://www.mapbiomas.org/map#transitions) and thus the Brazilian government has not included that biome in deforestation reduction, we assume $A_{BAU} = A_{NDC}$ for that biome.

(a) (b)



(c)

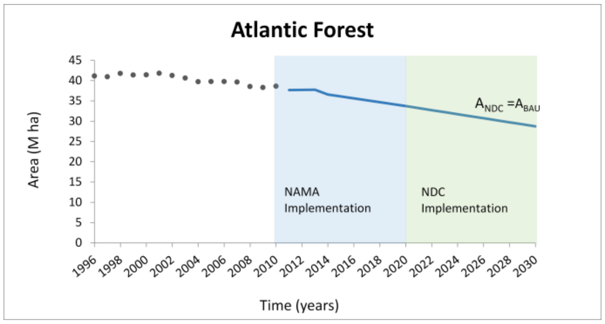


Figure 2: Pasture area scenarios for the main beef production biomes. (a) Amazon; (b) *Cerrado*; and (c) Atlantic Forest. Time series (observed data) are represented as dots; the baseline projection (A_{BAU}), blue curve; and the NAMA + NDC implementation scenario (A_{NDC}) orange curve.

Analogously to pasture estimates, beef production scenarios consist of historical data from 1996 to 2014 and projections for 2015-2030. Historical beef production was derived from national-level estimates (CNPC, 2016). National level projections (Gouvello *et al.*, 2011) were calibrated for continuity with the historical series from CNPC (2016). Brazil's total production (D_t) was allocated to each of the biomes assuming beef productivity as proportional to the biome stocking rate of the IBGE 2006 Census data (IBGE, 2015):

$$D_{b,t} = \sigma_b D_t \quad (3)$$

and

$$\sigma_b = \frac{P_{b,t} s'_b}{\sum_b P_{b,t} s'_b} \quad (4)$$

Where σ_b represents the proportion of national production allocated to biome *b*; $D_{b,t}$, represents the beef production and demand projections of biome *b* in year *t*, respectively for $1995 < t < 2015$ and $t > 2014$; and s'_b represents the stocking rate of biome *b* relative to the national average of 2006.

3.2 Intensification scenarios

The analysis assumes four intensification scenarios used to investigate the effects of NAMA accomplishment on the NDC restoration target, beef production, and whether intensification is based on pasture restoration alone, or combined with animal efficiency measures (supplementation and feedlot finishing). Table 2 describes scenarios characteristics.

Table 2: Agricultural Intensification scenarios.

Scenarios	**Deforestation targets (NAMA and NDC)**	**Pasture intensification (NAMA)**	**Pasture intensification (NDC)**	**Reduced production**	**Animal efficiency measures**	**Pasture area**
SBAU	No	No	No	No	No	A_{BAU}
SLC1	Yes	Yes	Yes	No	Yes	A_{NDC}
SLC2	Yes	No	Yes	Partially	No	A_{NDC}
SLC3	Yes	No	Yes	Partially	Yes	A_{NDC}

SBAU is the baseline scenario and assumes baseline deforestation rates of A_{BAU} projections, thus demand is met at the cost of pasture expansion over natural vegetation. The low carbon scenarios, SLC1 to SLC3 assume full accomplishment of the NAMA and NDC deforestation target. In SLC1, the livestock sector fully meets demand projections by pasture intensification (restoration) and by increasing key animal efficiency measures: feedlot, concentrate and protein supplements.

SLC2 assumes the NAMA restoration target fails, and pasture productivity remains constant over the NAMA period (2010-2019), no animal efficiency measures are taken, apart from feedlot finishing, which is kept constant (10% of total herd). Since both pasture and animal efficiency intensification measures are kept fixed in SLC2, the NAMA and NDC deforestation targets are met at the cost of reducing beef production. SLC3 is analogous to SLC2 but intensification through the adoption of the animal efficiency measures is allowed over the NAMA and NDC period.

3.3 Modelling overview

Two models were employed to improve the robustness of the calculation of the restoration area. Both models rely on different approaches and sets of assumptions, and convergence of results would be an indication of robustness of the strategy.

Demand Constrained Restored Area model (DCRA) is a single equation model explaining restoration area as a function of a predicted increase in demand, increasing animal efficiency, and total pasture area variation. The second model EAGGLE (The Economic Analysis of Greenhouse Gases for Livestock Emissions - de Oliveira Silva et al., 2015a, 2016), is a bio-economic linear programming model focused on profit maximization through optimization of pasture degradation and restoration processes.

EAGGLE simulates national livestock production as a whole cycle beef production farm (cow-calf, stocking and finishing), accounting for herd dynamics, financial resources, feed budgeting, land use, pasture recovery dynamics, crops and soil carbon stocks. The model optimizes use of farm resources while meeting exogenous demand projections.

The DCRA model treats restoration as a binary process, whereas EAGGLE defines a set of direct restoration practices for pasture formation, each comprising a different level of application; i.e. soil inputs and machine operations. The restoration area is thus defined as the sum of the adoption rate of the individual restoration practices over the targeted NDC decade 2020-30. EAGGLE was also employed for cost-effectives analysis; generating estimates of average direct restoration costs per hectare (costs of technologies), and GHG mitigation potential in terms of avoided deforestation and soil organic carbon sequestration through improved grasslands.

3.4 DCRA model

The DCRA model (Equation 13) was developed to estimate the total restored area required to meet a percentage growth in beef demand and reduced land availability. The model considers two grassland quality levels: degraded and productive, characterized by their average stocking rates. Accordingly, an increase in the total stocking rates is possible only by increasing the proportion of productive pastures. Over the 2020-30 period any increase in livestock demand can be met by increasing stocking rates and by an increase in animal productivity (i.e. carcass yield).

3.4.1 DCRA – mathematical derivation

Let *N(t)* be the number of animals (heads -hd) in any time instant *t*. *N(t)* can be written as a product of stocking rates and pasture area:

$$N(t) = s_D D(t) + s_R R(t) \quad (5)$$

Where s_D and s_R are respectively the stocking rates (head per hectare –hd.ha^{-1}) of degraded and productive pastures. *D(t)* and *R(t)* (ha) are the area of degraded and productive pastures in year *t*, respectively. *D(t)* and *R(t)* are defined so that:

$$\mathrm{A(t)} = \mathrm{D(t)} + \mathrm{R(t)} \quad (6)$$

Where *A(t)* is the total area in year *t*.

Substituting (6) in (5):

$$\mathrm{N(t)} = \mathrm{s_D A(t)} + \mathrm{R(t)}\left(\mathrm{s_R} - s_D\right) \quad (7)$$

Taking the derivative of *N(t)* in relation to *t*, we have:

$$\frac{\partial N}{\partial t} = s_D \frac{dA}{dt} + \left(s_R - s_D\right)\frac{dR}{dt} \quad (8)$$

Assuming that any change in *R(t)* is due to pasture restoration, i.e. grassland area can be removed only from degraded pastures, the restoration area is equivalent to *dR/dt*. Rearranging (8):

$$\Rightarrow \frac{dR}{dt} = \frac{\frac{\partial N}{\partial t} - s_D \frac{dA}{dt}}{\left(s_R - s_D\right)} \quad (9)$$

In addition to (5), *N(t)* can also be written as a function of beef demand and animal productivity:

$$\mathrm{P(t)} = \mathrm{C(t)N(t)} \quad (10)$$

Where *P(t)* represents beef production in year *t* (in tonnes of carcass weight equivalent – t CWE) and *C(t)* is the production per animal (CWE per head – t CWE.hd^{-1}). Applying the derivative of *P(t)* in relation to *t*:

$$\frac{\partial P}{\partial t} = N(t)\frac{dC}{dt} + C(t)\frac{dN}{dt} \quad (11)$$

Rearranging (11)

$$\frac{dN}{dt} = \frac{1}{C(t)}\left(\frac{\partial P}{\partial t} - N(t)\frac{dC}{dt}\right) \quad (12)$$

Substituting (8) in (5):

$$\Rightarrow \frac{dR}{dt} = \frac{\frac{1}{C(t)}\left(\frac{\partial P}{\partial t} - N(t)\frac{dC}{dt}\right) - s_D\frac{dA}{dt}}{\left(s_R - s_D\right)} \quad (13)$$

Where *dR/dt* represents the recovered pasture area over the period 2020-30 , *δP/δt* is the predicted change in production, *N(t)* and *P(t)* are respectively the initial herd and production, s_D and s_R are the stocking rates of degraded and restored pastures, respectively, *dC/dt* represents the gain in animal productivity, and *dA/dt* is the predicted change in total area.

dC/dt can be written as:

$$\frac{\mathrm{dC(t)}}{\mathrm{dt}} = kC(t) \quad (14)$$

Where *k* (year^{-1}) is the gain in animal productivity over *dt* relative to *C(t).*

Eq. 13 (DCRA model) provides a straightforward estimate of the restoration area over a period of time *dt* and is obtained as a function of predicted change in production (*δP/dt*), initial herd (*N(t)*), initial production (*P(t)*), stocking rates of degraded and restored pastures (s_D and s_R), relative gains in animal productivity (*k*), and predicted change in total area (*dA/dt*). The values used for the aforementioned parameters and variables are presented in Table 3.

Table 3: Assumed variable and parameter values.

Variable/parameter	**Values (SLC1)**	**Values (SLC2)**	**Values (SLC3)**	**Unit**	**Reference**
dP/dt	0.173	0.313	0.313	$Mt.yr^{-1}$	(Gouvello *et al.*, 2011)
P(t0)	11.40	10.00	10.00	$Mt.yr^{-1}$	(Gouvello *et al.*, 2011)
N(t0)	215.90	188.70	188.70	Mhd	(Gouvello *et al.*, 2011)
C(t)	0.053	0.053	0.053	$t.hd^{-1}$	(CNPC, 2016)
dA/dt	-1.00	-1.00	-1.00	$Mha.yr^{-1}$	(Gouvello *et al.*, 2011)
s_D	0.50	0.50	0.50	$hd.ha^{-1}$	(IBGE, 2015)*
s_R	2.00	2.00	2.00	$hd.ha^{-1}$	(IBGE, 2015)*
K	0.007	0.000	0.007	yr^{-1}	(CNPC, 2016)

* Based on (IBGE, 2015) stocking rates frequency.

3.5 The EAGGLE model

EAGGLE optimizes the use of farm resources (capital, cattle, land) while meeting annual demand projections and maximizing profit (gross margin). EAGGLE treats the biomes Amazon, *Cerrado* and Atlantic Forest as independent systems, i.e. no cattle transfer is assumed among the biomes and beef production is simulated independently with each biome treated as a single farm. The model simulates feedlot finishing and cattle supplementation allowing for the reduction of the finishing time. EAGGLE was implemented in AIMMS algebraic language, comprising approximately 23 k variables and 21 k constraints for a 25 years planning period, and was solved through the barrier method by the CPLEX solver (CPLEX, 2009).

3.5.1 Restoration practices

EAGGLE contains detailed representation of grassland management decisions, i.e. pasture degradation and restoration, and changes in soil organic carbon. Full description of the model is presented as supplementary information in De Oliveira et al., (2016).

Table 4 shows some examples of inputs and farm operations associated with restoration practices applicable to Brazilian degraded pastures. Full description containing all soil inputs and farm operations (e.g., in kg per hectare) are presented as supplementary information. The model optimizes pasture management based on decisions on whether to restore, maintain or degrade a pasture level defined in Table 4.

Table 4: Examples of pasture type formation (level of technology) and productivity (dry matter per area) for the Brazilian *Cerrado*.

Pasture level/practice	Pasture formation (illustrative description)[1]	Cost of technology (US$ 2012 per hectare)	Productivity (tonnes of dry matter per hectare year)[2]	Soil carbon equilibrium (tonnes per hectare)[3]
P1	Mowing + dolomitic limestone + single phosphate + *brachiaria* seeds + micronutrients + 90kg of N	767	19.6	84.3
P3	Mowing + dolomitic limestone + single phosphate + *brachiaria* seeds + micronutrients + 45kg of N	617.1	17.6	82.7
P5	Mowing + dolomitic limestone + single phosphate + *brachiaria* seeds	367.7	12.6	62.3
P7	Mowing +dolomitic limestone + single phosphate	137.1	8.7	45.2
P9	Dolomitic limestone + Mowing	42.5	5.8	32.4
P11	No intervention[4]	0	3.9	26.1

[1] This table presents examples of inputs and machinery operations associated with restoration practices. Full description is presented as supplementary information

[2] Annual dry matter accumulation rates are presented for illustration; EAGGLE uses seasonal productivity curves for the biomes using the Invernada software (Barioni, 2011).

[3] Soil organic carbon equilibrium values were calculated exogenously using simulations from the CENTURY model (Parton *et al.*, 1987), applied to *Cerrado* biophysical characteristics and using the annual dry matter accumulation rates calculated for each pasture category.

[4] *P11* represents pasture at minimum productivity level (ecosystem equilibrium).

3.5.2 Pasture degradation

Pasture degradation can be defined as the gradual loss of vigour, productivity and natural capacity for recovery to sustain production and quality as feed, and to withstand detrimental effects from insects, diseases and weeds (Macedo and Zimmer, 1993).

To represent the degradation process the model imposes a deterministic decline in dry matter productivity (DMP) with time. DMP levels (for example, in tonnes of dry matter per hectare year) are represented by $\Omega = \{P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,P11\}$. As the symbols are ordered in decreasing levels of DMP, the degradation process is represented as the annual transfer between consecutive levels, i.e., *P1* degrades to *P2* after one year of formation of pasture *P1*, if no interventions are undertaken; *P2* degrades to *P3* in the following year, and so forth, until *P10*, which degrades to *P11*, the minimum degradation level (ecosystem equilibrium), thus *P11* “degrades” to *P11*. Because there are 11 DMP levels and each level is one-year “distance” from its consecutive, the whole degradation process takes 10 years.

3.5.3 Pasture restoration area

Analogously, pasture restoration is represented as the transfer (in hectares) of a given DMP to a more productive state, for example from *P3* to *P1* or *P11* to *P5*. Table 5 represents the cost matrix of restoration. The diagonal represents the pasture maintenance cost (improvements to prevent degradation) and the values below the diagonal are the restoration costs. Table 5 values ($c_{p,q}$) can be read as the cost to transfer one hectare of a pasture with DMP *p* to pasture with DMP *q*.

Table 5: Cost of restoration management options (US$.ha^{-1})*

	$c_{p,q}$ (US$.ha^{-1})										
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
P1	130.8										
P2	178.7	108.8									
P3	226.7	156.7	86.7								
P4	257.4	187.4	117	52.2							
P5	288	218	148	82.8	17.6						
P6	375.9	305.9	236	171	105	14.3					
P7	463.8	393.8	324	259	193	102	11				
P8	517.4	447.4	377	312	247	156	64.6	8.86			
P9	571	501	431	366	301	209	118	62.5	6.7		
P10	590.1	520.1	450	385	320	228	137	81.6	26	3.4	
P11	609.1	539.1	469	404	339	248	156	101	45	22	0

* US$ are expressed in 2012 values (1 US$-2012 is equivalent to 2.04 Brazilian reals (R$) -2012) [a]

EAGGLE allows for fractions of pasture area to be restored to different DMP levels, e.g., any fraction of pasture *P5* could be restored to *P1*, other fractions to *P2* and *P5*, and a fraction

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[a] http://www.exchangerates.org.uk/USD-BRL-31_12_2012-exchange-rate-history.html

may even degrade to *P6*. Let $X_{t,p,q}$ be the pasture area that is transferred (restored) from pasture *p* to pasture *q* in year *t*; where *p* and *q* in *Ω;* The total recovered area in a given year *t* is given by:

$$R_t = \sum_{(p,q)|p>q} X_{t,p,q} \qquad (15)$$

By imposing p > q, the sum over the pair (*p*,*q*) accounts for any area that is improved in terms of DMP in a given year *t*. Thus, the restoration area over 2020 to 2030 is given by:

$$R = \sum_{t=2020}^{2030} R_t \qquad (16)$$

The restoration area is therefore defined as the optimal adoption level of direct restoration practices under the scenarios SLC1 to SLC3.

The annual cost of restoration is represented as:

$$RC_t = \sum_{(p,q)|p>q} c_{p,q} X_{t,p,q} \qquad (17)$$

Where $c_{p,q}$ are the values in Table 5. To represent the NDC policy intervention, the model assumes unrestricted credit availability in the first year of production. Thus the restoration costs (RC_t) provides an estimate of demand for ABC credit.

2.5.4 Soil organic carbon dynamics

Based on equilibrium values (Table 4) and parameters that represents bioclimatic conditions, the model dynamically simulates SOC accumulation depending on pasture management by using equation 18:

$$c_{t,p} = c_{t-1,p} + \rho_p(\varepsilon_p - c_{t-\text{`},p}) \quad (18)$$

Where $c_{t,p}$ is the SOC stock of pasture *p* in year *t* (in tonnes per hectare); ρ_p is the fraction of SOC which is lost by plant respiration of pasture *p*; ε_p is the SOC at equilibrium of DMP *p*. Eq. 18 estimates SOC at any time *t*. The parameter ρ_p was obtained exogenously by calibrating against the CENTURY model (Parton et al., 1987). See De Oliveira et al. (2017) for derivation of Eq. (18).

3.6 Animal efficiency measures

Animal efficiency measures represented in the EAGGLE model are feedlot finishing, concentrate and protein supplements. The measures are restricted to steers. For feedlot, the analysis assumed a minimum adoption rate to 10% of the total finished cattle, in accordance to current adoption (ANUALPEC, 2013), while no minimum adoption rate for concentrate and protein supplementation is assumed. Supplements for the animal efficiency formulation are based on soybeans, corn (silage) and corn (grain), mineral salt, NaCl and urea. Crops used in supplements are produced endogenously to the model. Animal efficiency measures, modelling and details of ration formulation are presented in De Oliveira Silva et al. (2015b).

3.7 Sensitivity analysis

Sensitivity analysis considered how restoration area varied with demand variations of -20%, -10%, 10% and 20% relative to baseline demand by 2030, in terms of kg of carcass-weight equivalent.

3.8 Emissions accounting

EAGGLE estimates GHGs using emissions factors for direct emissions and from life-cycle assessment (LCA). GHGs associated with farm activities are: (a) CH_4 from cattle enteric fermentation (CH_4 from excreta is not accounted); (b) N_2O from cattle excreta; (c) N_2O from N fertilization conversion; (d) CO_2 from deforestation using average biome-specific natural vegetation biomass; (e) CO_2 from pasture degradation; and (f) LCA factors for inputs and farm operations applied in land use change and restoration practices. Modelling details and emissions factor values for (a) to (c), (e) and (f) can be found in (de Oliveira Silva *et al.*, 2016). Values used for (d) are 170 t $C.ha^{-1}$, 34.6 t $C.ha^{-1}$ and 110 t $C.ha^{-1}$ respectively for the Amazon, *Cerrado* and Atlantic Forest (Brazil, 2010b).

3.9 Bioeconomic data

Costs related to the restoration practices specific to the *Cerrado* are presented in Table 5. Full details of applied inputs (soil chemical treatment) and farm operations (soil mechanical treatment) can be found as supplementary information. Based on historical time series (Conab, 2016) restoration costs for the Amazon were estimated as 15% higher than the *Cerrado* and costs for planting soybean and corn were respectively 4% and 8% higher than *Cerrado* costs.

Restoration costs for the Atlantic Forest were assumed equal to *Cerrado*, cattle prices in the Amazon and Atlantic Forest were respectively 4% higher and 4% lower than for the *Cerrado* (Conab, 2016).

Pasture productivity for the formations *P1* to *P11* in the biomes were estimated using the methodology detailed in (de Oliveira Silva *et al.*, 2016; de Oliveira Silva *et al.*, 2017), using the Invernada software (Barioni, 2011), which works with monthly average historical climate data and amounts of N applied to estimate potential accumulation rates for the main grass species in Brazil.

4. Results

The restoration target that guided the livestock contribution to the NDC assumed full accomplishment of the NAMA intensification, i.e. scenario SLC1.

Under SLC1, the DCRA model suggests over the period 2020-30, 16.20 Mha of restoration is necessary to meet demand and the zero deforestation target by 2030. For the same scenario, EAGGLE estimates the nationwide optimal restoration as 18.42 Mha over the same period, 8.91 Mha to be restored in the *Cerrado*, and 5.23 Mha and 4.28 Mha in the Amazon and Atlantic Forest respectively, combined with an average of 33% of slaughtered cattle under energy concentrate supplements (Table 6).

Table 6 shows the restoration target depends on whether pasture intensification starts before the NDC, during the NAMA period (2010-2020), or whether the NAMA fails, and thus pasture restoration starts only with the NDC (2020-2030). In the latter, the nationwide restoration target could reach up to 48.0 Mha and 54.6 Mha over 2020-30, respectively for SLC3 and SLC2. The DCRA model suggests 33.9 Mha and 42.7 Mha, respectively for SLC3 and SL2.

Table 6: Herd estimates, restoration area, costs and animal efficiency measures adoption rates by biome.

Scenario	Variable, avg 2020-2030	Cerrado	Amazon	Atlantic Forest	Brazil
SLC1	herd (M heads)	91.69	65.90	46.92	204.52
	Recovered area (M ha.yr^{-1})	**0.89**	**0.52**	**0.43**	**1.84(1.51)***
	Restoration costs (M US\$2012.yr^{-1})	226.61	148.42	68.42	443.46
	Feedlot adoption rate (% of herd)	10.00	10.00	10.00	10.00
	Concentrate adoption rate (% of herd)	31.00	36.00	33.00	33.33
	Protein adoption rate (% of herd)	3.00	0.00	0.00	1.00
SLC2	herd (M heads)	91.05	68.01	46.64	205.70
	Recovered area (M ha.yr^{-1})	2.45	1.51	1.51	5.46(4.27)
	Restoration costs (M US\$2012.yr^{-1})	808.17	287.86	467.04	1,563.07
	Feedlot adoption rate (% of herd)	10.00	10.00	10.00	10.00
	Concentrate adoption rate (% of herd)	0.00	0.00	0.00	0.00
	Protein adoption rate (% of herd)	0.00	0.00	0.00	0.00
SLC3	herd (M heads)	91.38	67.35	46.52	205.26
	Recovered area (M ha.yr^{-1})	2.16	1.37	1.26	4.80 (3.39)
	Restoration costs (M US\$2012.yr^{-1})	685.12	266.45	379.44	1,331.01
	Feedlot adoption rate (% of herd)	10.00	10.00	10.00	10.00
	Concentrate adoption rate (% of herd)	26.00	35.00	25.00	28.67
	Protein adoption rate (% of herd)	8.00	1.00	9.00	6.00

* DCRA results

Estimated average restoration costs per recovered hectare under SLC1 (i.e. total costs divided by recovered area in Table 6) are 254.6 US\$. ha.$^{-1}$, 284.3 US\$. ha.$^{-1}$ and 241.0 US\$ .ha.$^{-1}$, respectively for the *Cerrado*, Amazon and Atlantic Forest. Table 6 suggests around US\$ 0.44 billion per year are required to meet the 18.4 Mha restoration area from 2020-30.

Under SCL1 production equals demand but scenarios SLC2 and SLC 3 indicate the impact on beef production if pastures are not intensified prior to the NDC restoration target, i.e. if the NAMA fails. Under SLC2, since pasture productivity levels are assumed fixed from 2010 to 2019, production would reduce by 17%, 14% and 20% during that period, respectively for the *Cerrado*, Amazon and the Atlantic Forest. Under SLC3, since animal efficiency measures are adopted (Table 6), the reduction on production would be 7%, 8% and 9%, respectively for the *Cerrado*, Amazon and the Atlantic Forest.

The total recovered area presented in each biome (Table 6) consists of a set of different pasture restoration technologies, depending on the target level of restoration and thus use of inputs (e.g., seeds, nutrients, fertilizers). Figure 3 shows the optimal (minimum cost) adoption rate of the restoration practices for each biome under SLC1.

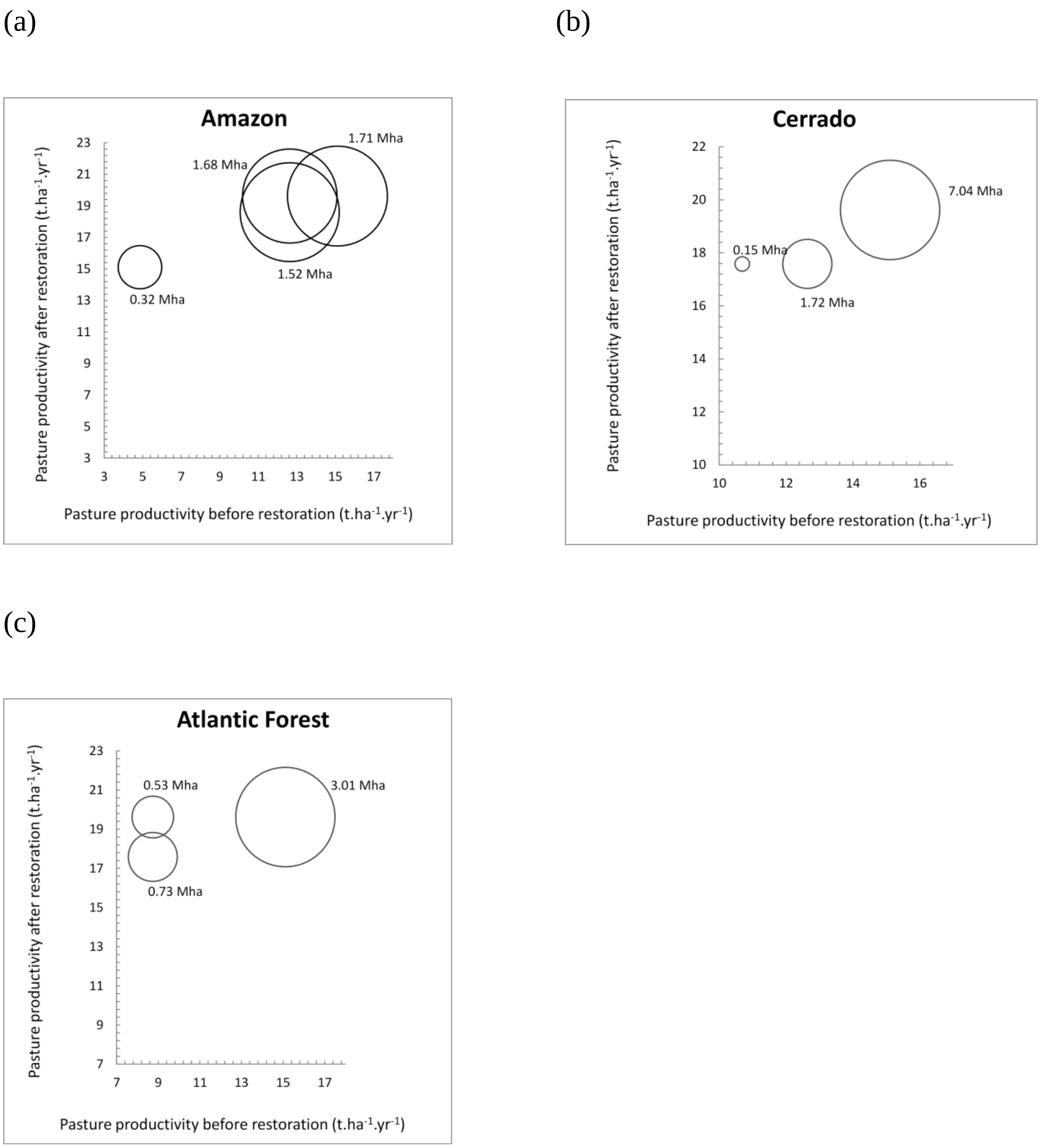


Figure 3: Types of pasture restoration applied by biome under SCL1: (a) Amazon; (b) *Cerrado*; and (c) Atlantic Forest. The x-axis represents the initial value of pasture forage productivity (DMP); the y-axis represents the DMP after restoration; the circle radius represents the area of a restoration level applied.

Figure 3a shows that in the Amazon, 92% of the 5.23 Mha of restoration area from 2020-30 is based on restoring pastures with initial forage productivity (DMP) of between 12.6 tonnes of dry matter per ha year (t-DM.ha^{-1}.yr^{-1}) to 15.6 t-DM.ha^{-1}.yr^{-1} to between 18.6 to 19.62 t-DM.ha^{-1}.yr^{-1}. Only 0.32 Mha are restored from severely degraded pastures (*P11*), with DMP of around 5 t-DM.ha^{-1}.yr^{-1}, to DMP of 15,2 t-DM.ha^{-1}.yr^{-1}. Similarly, in the *Cerrado* and Atlantic Forest around 90% of the 8.9 Mha and 4.28 Mha, respectively, of restoration area are based on restoring pastures with initial DMP of 15 t DM.ha^{-1}.yr^{-1} to 19.6 t DM.ha^{-1}.yr^{-1}.

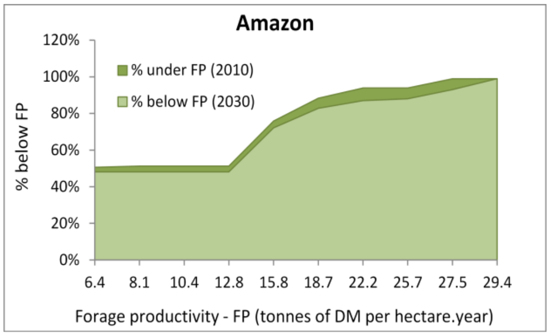
There is currently no standard quantitative definition of pasture degradation and available estimates of the extent of degradation are highly aggregated. Here we model pasture degradation by imposing an intertemporal decline in forage DMP for the areas of pastures that are not restored (*P1* to *P11* for a full degradation cycle). A threshold DMP value can be assumed so that anything below this can be considered as degraded pasture. EAGGLE can thus estimate the proportion of pasture degradation in Brazil based on historical beef production, pasture area, bio economic and climate data, and by assuming that farmers seek to maximize profit, i.e., minimizing restoration costs.

Figure 4 shows the proportion of degraded pasture according to different DMP threshold values (tonnes of dry matter per hectare per year) for the biomes by 2010 before NAMA implementation, and by 2030 when the restoration and deforestation targets are accomplished.

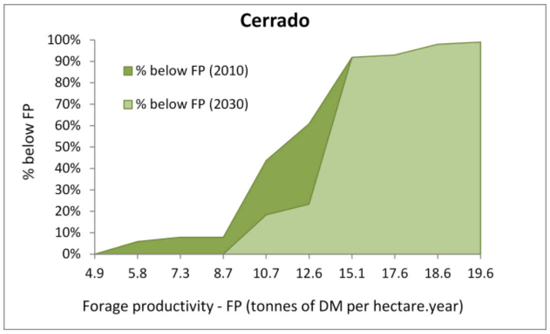
One possible assumed DMP threshold value is that equivalent to the initial pasture productivity for recently cleared natural vegetation, thus any DMP below that initial value may be considered as degraded. In this modelling exercise, this value corresponds to pastures DMP *P5* and *P6*, the equivalent to10.7 t-DM.ha^{-1}.yr^{-1} to 12.6 t-DM.ha^{-1}.yr-1 for the *Cerrado* and

Atlantic Forest, and from 15.8 to 18.7 t-DM.ha^{-1}.yr^{-1} for the Amazon, Fig. 3 shows that between 44% to 61%, 76% to 88% and 47% to 61% of pastures in the *Cerrado*, Amazon and Atlantic Forest, respectively, present some level of degradation. This is consistent with available estimates of between 50% and 80% (Macedo et al., 2014; Peron and Evangelista, 2004). The modelling results show that by 2030 after NAMA and NDC implementation the proportion of degraded pastures would reduce from 38% to 25%, 83% to 72% and from 18% to 16% in the *Cerrado*, Amazon and Atlantic Forest, respectively.

(a)



(b)



(c)

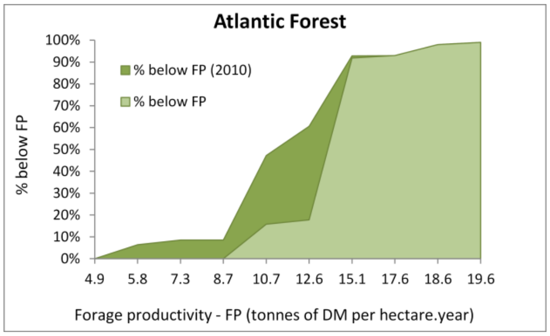


Figure 4: Percentage of degraded pastures estimates for: (a) Amazon; (b) *Cerrado*; and (c) Atlantic Forest. The y-axis indicates the percentage of pastures with forage productivity below the DMP value in the x-axis.

Sensitivity analysis shows how the restoration area is sensitive to demand. Figure 5 shows that reducing the projected 2030 demand by 10% and 20% reduces the 18.2 Mha by 15% and 33%, respectively. Increasing demand by 10% and 20% would require an increase of 14% and 57% in the restoration area respectively.

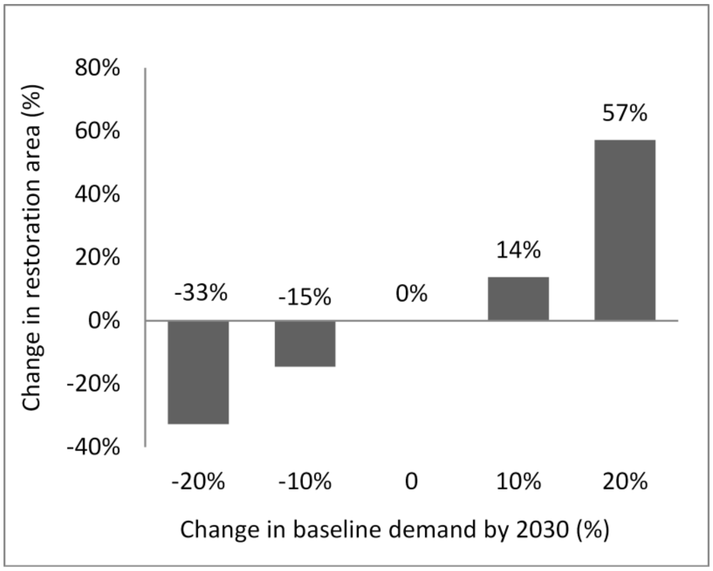


Figure 5: Sensitivity analysis of the 18.2 M ha of restoration area (SLC1) against change in beef demand.

Figure 6 shows emissions trajectories based on Fig. 2 pasture scenarios and the SLC1 intensification scenario. Amazon emissions up to 2005 (Fig. 6a) were largely dominated by pasture expansion, i.e. livestock-associated deforestation, subsequently decreasing substantially. If pasture expansion rates were the average observed for the period 1995-2005, estimated baseline deforestation rates imply Amazon emissions will average 1140 Mt CO_2e.yr^{-1} from 2011-2030. In a zero deforestation scenario this reduces to 165.9 Mt CO_2e.yr^{-1}.

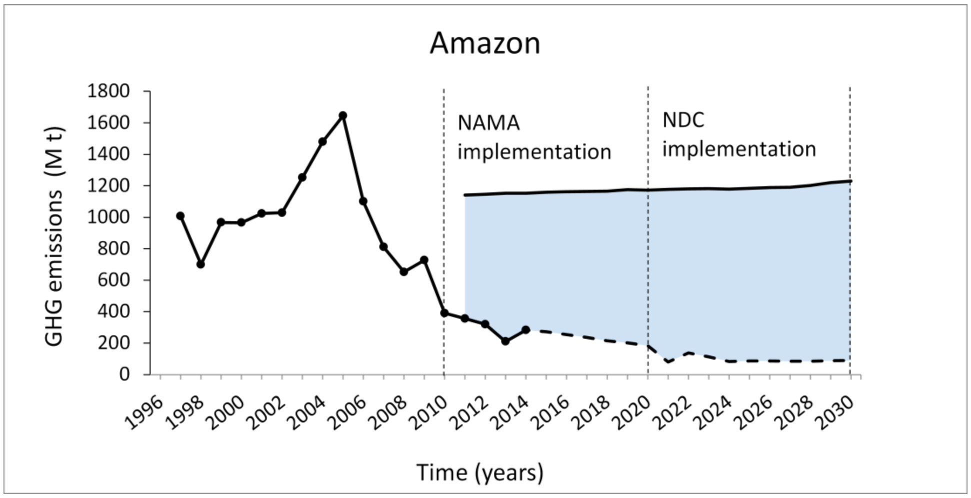
Cerrado livestock emissions (1996-2010) were also largely dominated by pasture expansion up to 2009 (Fig. 6b). Average estimated emissions for the period 1996-2010 were around 150 Mt CO_2e.yr^{-1}, decreasing to 102 Mt CO_2e.yr^{-1} and 54 Mt CO_2e.yr^{-1} (2011-2030), for SBAU and SLC1, respectively.

Livestock emissions in the Atlantic Forest biome are roughly half those from the *Cerrado* for the whole 1996-2030 period (Fig.6c). Estimated emissions were dominated by pasture expansion in 1998, 2001 and 2010. Averaging 84.3 Mt CO_2e.yr^{-1}. Atlantic Forest emissions are projected to fall to 33.4 Mt CO_2e.yr^{-1} from 2011 to 2030.

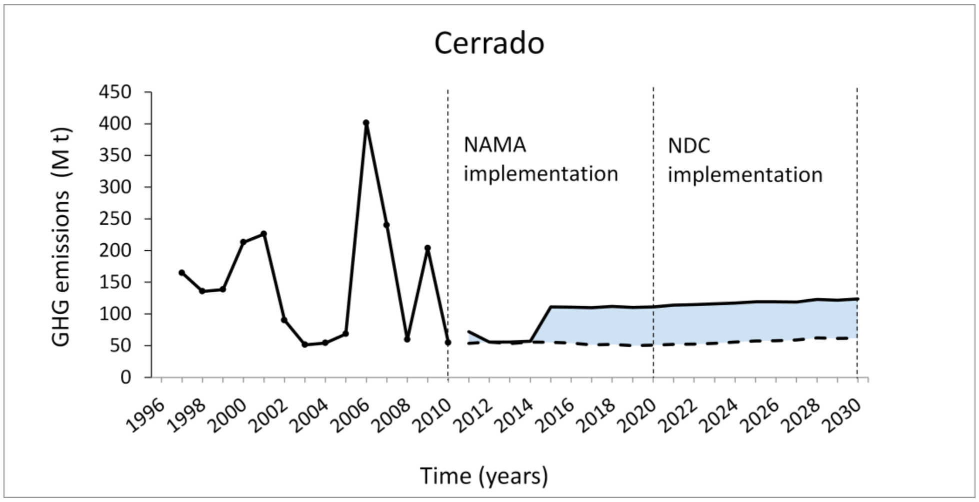
Fig. 6d shows the emissions trajectory and the full mitigation potential from the livestock sector NAMA and NDC (SLC1). Under baseline deforestation rates, emissions (2011 – 2030) would average 1130 Mt CO_2e. yr^{-1}, while NAMA and NDC implementation could reduce this to 165 Mt CO_2e.yr^{-1}; equivalent to around 80% of livestock emissions (85% in the Amazon and 43% in the *Cerrado*). This reduction translates into 1150 Mt CO_2e.yr^{-1} (2011 - 2030) (Fig. 2e), with 97% arising from reduced pasture expansion in the Amazon and the *Cerrado*.

If the NAMA deforestation target fails, the livestock sector would emit around 1.31 Gt CO_2e by 2020. Meeting the NAMA target means that figure would drop to around 266.4 Mt CO2e by 2020, the equivalent to an 80% reduction. The 266.4 Mt CO_2e would further reduce to 178.3 Mt CO_2e by 2030 if the NDC zero deforestation target is met.

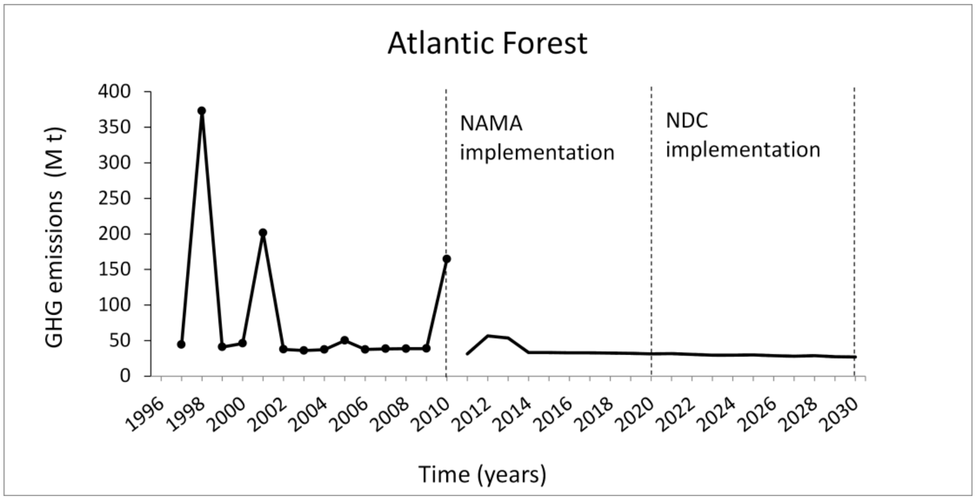
(a)


Amazon
GHG emissions (M t)
1800
1600
1400
1200
1000
800
600
400
200
0
NAMA implementation
NDC implementation
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2022
2024
2026
2028
2030
Time (years)

(b)


Cerrado
GHG emissions (M t)
450
400
350
300
250
200
150
100
50
0
NAMA implementation
NDC implementation
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2022
2024
2026
2028
2030
Time (years)

(c)



(d)

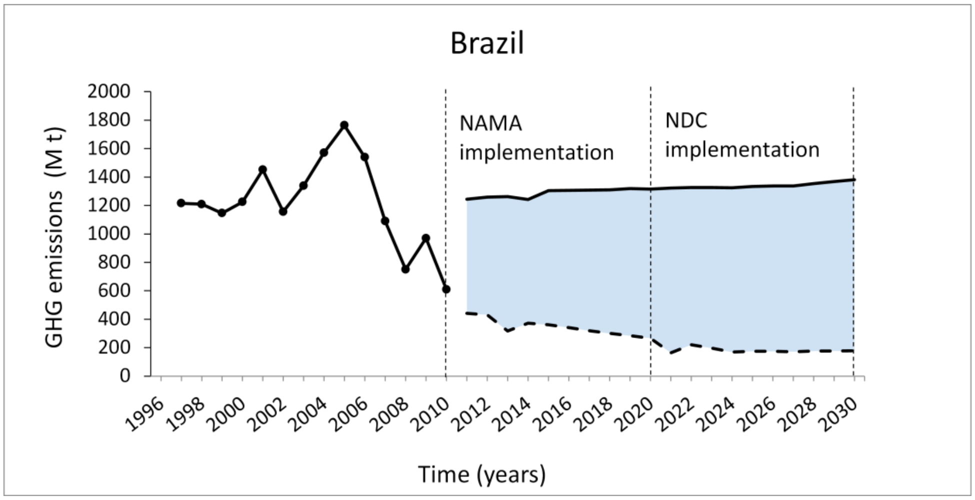


Figure 6: GHG emission estimates based on observed data from 1996-2010 (dots) and projections under baseline (solid lines), and NAMA and NDC scenarios (dashed lines) for (a) the Amazon; (b) the *Cerrado*; (c) the Atlantic Forest and (d) Brazil.

5. Discussion

The 16.2 - 18.4 Mha estimates guided the proposal advanced by Brazil at COP21 (2015), with pasture restoration a key measure reconciling competing challenges. The estimates assume the NDC restoration target will follow on top of the NAMA intensification, plus increased adoption of animal efficiency measures (supplements and feedlot). This analysis identifies what is possible to achieve in terms of combining sustainable intensification with effective deforestation control policies in all three biomes.

The analysis suggests how effective SAI will be conditional on effective deforestation polices. Empirical evidence (Arima *et al.*, 2014; Macedo *et al.*, 2012; Lapola *et al.*, 2014; FAO, 2015; IBGE, 2015) supports the feasibility of the NDC, with the corollary of continued policies controlling deforestation (Arima *et al.*, 2014), plus the provision and adoption of funding for restoration and other intensification technologies through the ABC program. Our results suggest that the available ABC budget of US$1.7 billion in 2012 (Brazil, 2013) exceeds the average estimated restoration cost of US$ 0.44 billion. Note however that the estimates here are for optimal (minimum costs) restoration. If restoration were targeted disproportionately on more severely degraded pastures costs would increase significantly. Furthermore, this analysis excludes indirect restoration costs, including transportation of inputs to the farms and costs of extra skilled labour.

Despite the ABC programme, measure adoption may still be challenging, with evidence suggesting limited uptake due to the inherent risk-aversion among producers with respect to the liabilities, lack of skilled labour and bureaucracy attached to ABC credit (Latawiec et al., 2017).

This includes tenure requirements, alternative land use implications, and declaration of their emissions.

Brazil is not complacent about the livestock deforestation nexus and the apparent decoupling may only have been weakened temporarily. Recent official estimates from Brazil's National Institute for Space Research (INPE) in the Amazon (INPE, 2017) indicate that deforestation rates started to rise again, notably the period 2013-2016 saw the highest rates in 8 years (Tollefson, 2016). However, these are around 60-70% lower than the average deforestation rate for the period 1995-2005 (INPE, 2017), meaning the country could still be on track for meeting deforestation targets. This is largely due to a combination of effective public policies, increased monitoring, law enforcement, increasingly intensification and oriented to large-scale farming of trade commodities and private sector engagement, e.g., soybean moratoria (Arima *et al.*, 2014; Lapola *et al.*, 2014). These actions are likely to remain important (Zarin *et al.*, 2016).

6. Conclusion

GHG inventories and agricultural mitigation actions in most developing countries are based on simplistic emissions factors (Ogle *et al.*, 2014). These results suggest credible scenarios for the roles of agricultural intensification, greenhouse gases mitigation potential, deforestation control policy and land sparing.

Biophysical, economic and behavioural heterogeneities that characterise agricultural systems and land use change are a complication when attempting to include related emissions in policy targets. However, these sources are significant and Brazil's NDC is a bold statement of its scientific and intuitional commitment to reconciling key sustainability challenges via SAI. Our analysis points to the feasibility of the approach pending the role of complementary policies on deforestation and farm support. The intensification route by pasture restoration applies elsewhere in Latin America (e.g. Colombia), and potentially elsewhere in sub-Saharan Africa.

Acknowledgments

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