MODELLING SUSTAINABLE INTENSIFICATION IN BRAZILIAN AGRICULTURE

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Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and the work has not been submitted for any other degree or professional qualification.

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Table of Contents

Table of Contents ... iii
List of Figures ... v
List of Tables ... vi
Abbreviations and units ... viii
Thesis abstract ... x
Lay summary ... xi
Chapter 1 – Introduction ... 1
1.1 Background ... 1
1.2 Metrics and modelling approaches to sustainable agricultural intensification ... 2
1.3 The Brazilian Cerrado ... 4
1.4 Aims and objectives ... 6
Chapter 2 - Optimizing pasture restoration through improved restoration practices and rural credit ... 9
2.1 Abstract ... 10
2.2 Introduction ... 10
2.3 Methods ... 12
2.4 Results ... 30
2.5. Discussion ... 37
2.6. Conclusion ... 39
Chapter 3 - Developing Marginal Abatement Cost Curves for Brazilian beef production ... 41
3.1 Abstract ... 42
3.2 Introduction ... 42
3.3 Methods ... 44
3.4 Results ... 56
3.5 Discussion ... 61
3.6 Conclusion ... 62
Chapter 4 - Designing the livestock contribution to the Brazilian Intended Nationally Determined Contribution (INDC) ... 63
4.1 Abstract ... 64
4.2 Introduction ... 64
4.3 Methods ... 67
4.4 Results ... 75
4.5 Discussion ... 79
4.6 Conclusion ... 79

Chapter 5 - Changes in greenhouse gases emissions as a function of changes in Brazilian beef demand 81
5.1 Abstract 82
5.2 Introduction 82
5.3 Methods 84
5.4 Results 85
5.5 Discussion 90
5.6 Conclusion 91
Chapter 6 - Thesis conclusions 93
References 98
Appendix 1: Supplementary information 108
EAGGLE Mathematical description 108
Supplementary Tables 141
Supplementary Figures 161
Appendix 2: paper 1 163
Appendix 3: paper 2 172

List of Figures

Figure 2.1: Comparison of economic returns depending on initial degradation scenarios and access to ABC credit. 33

Figure 2.2: Pasture composition and associated forage productivity. 34

Figure 2.3: soil organic carbon stocks as a function of time and restoration practices. 35

Figure 2.4: Emissions intensity comparison for the restoration practices 36

Figure 2.5: Sensitivity analysis of ABC credit interest rate versus net present value, emissions intensity and beef productivity for FRP. 37

Figure 3.1: Baseline emissions of beef production in the Brazilian Cerrado 57

Figure 3.2: Share of the main GHG emissions sources from beef production in the Brazilian Cerrado...58

Figure 3.3: Marginal abatement cost schedule of key mitigation measures applicable to beef production in the Cerrado. 59

Figure 3.4: Mitigation measures adoption rate. 60

Figure 4.1: Brazilian main beef cattle production systems (biomes).....................................65

Figure 4.2: Estimates and projections of pasture area and GHG emissions pre and post NAMA and INDC implementation. 78

Figure 5.1: Brazilian Central Cerrado...84

Figure 5.2: Demand scenarios and sensitivity analysis 87

Figure 5.3: Long term GHG emissions analysis for the demand scenarios............................88

Figure 5.4: Emissions intensity as a function of demand scenario 89

Figure S1: Discrete representation of pasture degradation of Brachiaria Brizantha. 161

Figure S2:Comparison between beef production and pasture area using Brazilian agricultural Census (IBGE) and FAO estimates...161

Figure S3:calibrated values for k. 162

List of Tables

Table 1.1:Beef production share 5

Table 2.1: Symbols for indices and functions of sets used in the mathematical description of the model........ 14

Table 2.2: Symbols for Decision Variables 14

Table 2.3: Symbols and Values for Model Parameters 15

Table 2.4: Steer Bioeconomic Data 25

Table 2.5: Parameters for emissions factors estimation 26

Table 2.6: Pastures Accumulation Rates and Equilibrium C Stock Values in Function of Pasture Type (Brachiaria brizantha cv. Marandu) 27

Table 2.7: Cost of Pasture Restoration Management Optimization[a] 28

Table 2.8: Farm Annual Maintenance Costs[a]. 29

Table 3.1: Annual dry matter productivity and equilibrium C stock values in function of land use. 47

Table 3.2: Costs of pasture restoration practices and crops planting. 48

Table 3.3: Selected livestock mitigation measures. 53

Table 3.4: Rations (supplements) formulation and costs. 54

Table 4.1: Assumed values for the variables and parameters 71

Table 4.2: Description of pasture type formation and productivity for the Brazilian Cerrado. 72

Table 4.3: Beef demand and model results: herd estimates, restoration area and costs by biome........ 76

Table S1: Animals categories, Dry Mater Intake (DMI), average shrunk body weight 141

Table S2: Supplemented steers (age cohort), DM intake, weight, and emissions factors 143

Table S3:Amount of inputs and costs of pasture restoration 144

Table S4:Amount of inputs and costs of pasture maintenance 147

Table S5: Inputs and costs of plantation of corn for silage production 149

Table S6: Inputs and costs of plantation of corn for grain production....................................151

Table S7: Inputs and costs of plantation of soybeans production..154

Table S8: Farm annual maintenance costs..155

Table S9: List of LCA values according to inputs application and machinery operations. ...157

Table S10: Pasture area scenarios and associated deforestation..159

Table S11:Protein content, relative equivalence with beef and carbon footprint for Brazilian broiler meat. 160

Abbreviations and units

Low Carbon Agriculture (*Agricultura de Baixo Carbono)*	ABC
Average Dry Matter Productivity	ADMP
Carbon dioxide equivalent	CO_2e
Conference of the Parties	COP
Carcass weight equivalent	CWE
Demand Constrained Restoration Area	DCRA
Dry matter	DM
Dry matter productivity	DMP
Economic analysis of greenhouse gases from livestock emissions	EAGGLE
Emissions intensity	EI
Fractional Restoration Practice	FRP
Greenhouse gas emissions	GHG
Hectare	ha
High Pasture Productivity	HPP
Intended Nationally Determined Contributions	INDC
Intergovernmental Panel on Climate Change	IPCC
Intermediate Pasture Productivity	IPP
Life-cycle assessment	LCA
Left hand side	LHS
Low Pasture Productivity	LPP
Live weight	LW

Marginal abatement cost curve	MACC
Nationally Appropriate Mitigation Actions	NAMAs
Net present value	NPV
Pasture area time series	PATS
Brazilian reals	R$
Right hand side	RHS
Tonne	t
Mega tonne	Mt
Mega hectare	Mha
Giga tonnes	Gt
Kilogram	kg
Year	yr
Month	mth
Produced by farm	PBF
Abatement potential	AP
Cost effectiveness	CE
Grams	g

Thesis abstract

At the United Nations Framework Conference on Climate Change COP15 (2009) Brazil presented ambitious commitments or Nationally Appropriate Mitigation Actions (NAMAs), to reduce greenhouse gases emissions (GHGs) mitigation by 2020. At COP21 (2015), the country presented new commitments and a framework to achieve further mitigation targets by 2030 as so-called Intended Nationally Determined Contributions (INDCs). Both NAMAs and INDCs focus on the land use change and agricultural sectors, but the INDCs include a commitment of zero illegal deforestation in the Amazon by 2030. This research focuses on the contribution of the livestock sector to reducing GHGs through the adoption of sustainable intensification measures. A detailed linear programming model, called Economic Analysis of Greenhouse Gases for Livestock Emissions (EAGGLE), of beef production was developed to evaluate environmental trade-offs. The modelling encompasses pasture degradation and recovery processes, animal and deforestation emissions, soil organic carbon dynamics and upstream life-cycle inventory. The model was parameterized for the Brazilian *Cerrado*, Amazon and Atlantic Forest biomes and further developed for farm-scale and regional-scale analysis. Different versions of the EAGGLE model was used to: (i) Evaluate the GHG mitigation potential and economic benefit of optimizing pasture management through the partitioning of initially uniform pasture area; (ii) to define abatement potential and cost-effectiveness of key mitigation measures applicable to the Brazilian *Cerrado*; (ii) to demonstrate the extent of cost-effective mitigation that can be delivered by the livestock sector as part of INDCs, and to show a result that underpins the national INDC target of zero deforestation; and (iv) to evaluate the consequences of reducing (or increasing) beef production on GHGs in the Cerrado. Counter-intuitively, a sensitivity analysis shows that reducing beef consumption could lead to higher GHG emissions, while increasing production could reduce total GHGs if livestock is decoupled from deforestation.

Lay summary

The environmental impacts of livestock production in Brazil are mainly the loss of biodiversity and emissions of greenhouse gases due to forest clearing for pastures and the emissions of methane, a greenhouse gas that is around 21 times more powerful than CO2 in terms of causing global warming. On the other hand, Brazil is a major player in food production and accounts for around 15% of world beef production. Livestock and agriculture are key sectors in the Brazilian economy. To address the challenge of increasing production while reducing environmental impacts, scientists have proposed the sustainable intensification of agriculture, where intensification means production of more with less resources in ways that do not undermine our ability to produce food in the future. This thesis develops a detailed mathematical model to represent beef production systems in Brazil. The model is used to identify the best strategies to reduce emissions while meeting demand. The model considers emissions at all the stages of beef production, and was used to represent beef production in the Brazilian Cerrado, Amazon and Atlantic Forest biomes. Different versions of the model were used to: (i) Evaluate the GHGs mitigation potential and economic benefit of better pasture management; (ii) define abatement potential and cost-effectiveness of key mitigation measures applicable to the Brazilian Cerrado; (iii) demonstrate the extent of cost-effective mitigation that can be delivered by the livestock sector on the Brazilian commitments to reduce emissions by 2030, and to establish a result that underpins the INDC target of zero deforestation; and (iv) evaluate the consequences of reducing (or increasing) beef production on GHGs in the Cerrado. Counter-intuitively, a sensitivity analysis shows that reducing beef consumption could lead to higher GHG emissions, while increasing production could reduce total GHGs if livestock is decoupled from deforestation.

Chapter 1 – Introduction

1.1 Background

Recent anthropogenic emissions of greenhouse gases (GHG) are the highest in history and climate change is already causing widespread impacts on human and natural systems (IPCC, 2014). According to the Intergovernmental Panel on Climate Change (IPCC), if global warming exceeds 2°C by 2100, frequency of extreme climatic events is likely to increase significantly. The estimated cut in emissions to reach the 2°C target is around 40-70% of global GHGs by 2050 and subsequent zero net emissions by 2100 (IPCC, 2014).

Worldwide, the livestock sector alone is responsible for approximately 14.5% of all anthropogenic GHGs, and around 44% of livestock GHGs are in the form of methane (CH_4) from ruminant enteric fermentation (Gerber et al., 2013). Livestock mitigation options account for up to 50% of agricultural technical mitigation potential (Herrero et al., 2016). Mitigation and adaptation options include production or supply side measures, e.g., reducing animal life cycle, genetic improvement, reducing land demand for grazing animals, soil organic carbon (SOC) sequestration from improved grasslands and integration of crop-livestock-forest systems (de Oliveira Silva et al., 2015b; Gouvello et al., 2011; Herrero et al., 2016; Moran et al., 2011; Steinfeld et al., 2006), and demand-side, e.g., reduction of livestock product consumption (Bajželj et al., 2014; Garnett et al., 2013; Godfray et al., 2010; Hedenus et al., 2014) and production or supply side measures, e.g., reducing animal life cycle, genetic improvement, reducing land demand for grazing animals, increasing soil organic carbon (SOC) sequestration from improved grasslands and integration of crop-livestock-forest systems (de Oliveira Silva et al., 2015b; Gouvello et al., 2011; Herrero et al., 2016; Moran et al., 2011; Steinfeld et al., 2006).

In Brazil, livestock (mostly beef cattle) account for around 15% of national GHGs (Brasil, 2010). Data from the Official National Emissions Inventory (Brasil, 2010), show that while deforestation accounted for 57% of the 2.0 Gt CO_2e emitted by Brazil as a whole in 2005, this share decreased to 15% of the 1.2 Gt CO_2-eq total emitted in 2012. As land use change (deforestation) reduces, the share of beef cattle emissions increases.

Gouvello et al. (2011) estimated that increasing beef productivity could provide the land needed for the expansion of crops for food and biofuel production in a near-zero deforestation scenario, while meeting increasing livestock product demand, at least up to 2040. Such actions are likely to reduce GHG emissions by lowering methane per unit of product, by avoiding deforestation, and through increasing soil organic carbon stocks (Gouvello et al., 2010).

Brazilian beef systems are predominantly pasture-based; i.e., around 90% of cattle are pasture-fed only (Anualpec, 2013). Despite a significant productivity increase over the last three decades (Martha et al., 2012), challenges remain, both to reverse the economic losses from grassland degradation, and to accommodate growing demand while avoiding the conversion of natural habits. This challenge can be addressed by sustainable agricultural intensification (SAI). SAI is widely discussed as a response to the global grand challenge or 'perfect storm' (Godfray et al., 2014, 2010), but available literature is largely populated by conceptual work (Garnett et al., 2013; Godfray et al., 2014; Loos et al., 2014) that lacks of empirical models needed for policy evidence (De Oliveira Silva et al., 2016).

1.2 Metrics and modelling approaches to sustainable agricultural intensification

SAI has been advanced as an approach to address the issue of food security under the pressures of population growth, dietary shifts in developing countries and climate change (Garnett et al., 2013; Godfray et al., 2014). The basic principle of SAI relies on the process of producing more food from existing land in ways that place far less pressure on the environment, and do not undermine our capacity to continue producing food in the future (Garnett et al., 2013). The definition of SAI has been the subject of debate, with some arguing that SAI should include social sustainability and equity dimensions (Loos et al., 2014). In this sense, SAI indicators, or metrics, are necessary to measure and define the boundaries of what can be called SAI (Smith et al., 2016). Metrics are also important to guide modelling and evaluation of SAI at different scales. Smith et al (2016) provides a specific definition of SAI in terms of highlighting trade-offs and synergies between metrics relevant to smallholder systems. But this paper stops short of considering other relevant scales of analysis or the nature of models that can be used to optimize over different metrics.

Schils et al (2007) highlights the need for whole-farm modelling approaches to investigate SAI options. Whole-farm models are usually a combination of empirical and mechanistic modelling, and are adequate for GHG mitigation analysis as farm emissions generally consist of different GHGs (e.g. CH_4, N_2O and CO_2) from different sources. A whole-farm approach requires the consideration of at least two farm compartments, e.g., soil dynamics, animal dynamics, forage production.

The first step on developing a whole-farm model is to define the scope of the analysis, which requires stating the aims, boundaries and objectives of study (Schils et al., 2007). This would define the nature of emissions accounting, for example by considering only direct emissions within the farm or a life cycle assessment (LCA) approach, in the latter emissions associated with all stages of production are accounted (Thomassen et al., 2008). It also determines if LCA is attributional, when emissions are based on a fixed level of output (e.g., kg of beef per hectare-year) or consequential LCA, when marginal changes in the level of the system output (or demand) changes GHG emissions within the modelled system (Thomassen et al., 2008).

This work focuses on the ex-ante evaluation of key intensification measures, both in terms of GHG mitigation potential and cost analysis. Linear programming is an ideal tool for ex-ant evaluations through whole-farm modelling (Crosson et al., 2011). LP models have been widely used for agricultural decision making and for economic impact of agricultural policies (Britz and Witzke, 2012; Crosson et al., 2011; Dent et al., 2013; Janssen and van Ittersum, 2007; Lafayette and Zealand, 1982; Weintraub and Romero, 2006). Most farm models are single criteria, usually gross margin maximization (sales revenues minus variable costs). An alternative approach is multiple objective functions (Annetts and Audsley, 2002), but the applicability is contested due to the difficulty in accommodating conflicting objectives, which is generally solved by attributing subjective weights to each objective function (Chankong and Haimes, 2008). Since this work focused on the evaluation of mitigation measure adoption at farm and regional level, the analysis is based on the single criteria approach.

LP models are also limited in imposing a linearity to represent farm components. In the following analysis for example, farm fixed costs are proportional to the pasture area, and some investments costs of intensification measures are proportional to cattle numbers. Cattle and pasture dynamics (degradation and restoration) though, were modelled using linearization techniques, which allow for non-linear behaviours by using linear equations. At the regional scale the aggregation problem changes and gross margin maximization may not be justified since changes in the supply chain may affect prices (Crosson et al., 2011; Schils et al., 2007). Instead, at the regional scale the maximization of consumer and producer surplus and the use of partial equilibrium models are more appropriate to account for regional scale effects of market changes and public policies on agriculture (Havlík et al., 2011; Schils et al., 2007). Adding a partial equilibrium equation breaks the linearity of the models resulting in a quadratic-programming problem. In this work, however, we do not model partial equilibrium. This is because: (i) demand and supply are exogenous to our model; (ii) the relationship between demand and area is also exogenous, i.e., level of intensification and (iii) our study focuses on mitigation measure adoption with detailed representation of pasture management rather than market interactions. For example, chapter 5, intentionally analyses the effects of marginal change in projected demand on pasture management and GHG emissions while keeping all the other variables fixed.

In terms of systems heterogeneity modelling, spatially explicit modelling is recommended for models developed to address land use change dynamic (Britz and Witzke, 2012; GTAP, 2014; Havlík et al., 2011) and market interactions. The LP developed in this work models only beef production systems in Brazil. Furthermore, a spatially explicit version of the LP model would introduce the need of data that is currently unavailable in Brazil, including the specific micro regions that are calve-cow operations, fattening and finishing or complete cycle. The Pantanal biome (Brazilian wetlands) for example, generally produces calves for the Cerrado, but currently there is insufficient spatially explicit information and climatic and biophysical data that justifies spatially explicit modelling of Brazilian livestock systems.

1.3 The Brazilian Cerrado

Brazil is divided in six continental biomes: the Amazon, Cerrado, Caatinga, Atlantic Forest, Pantanal and Pampa (Table 1.1). This thesis focus on SAI options in the *Cerrado* core (central Brazilian savannah). The region is considered as central in Brazil's ascendance in global production (The Economist, 2010) and is still regarded as the most important region for expanding beef production in Brazil (Ferraz and Felício, 2010a). It is seen as a potential model for transforming other savannahs (Morris et al., 2012).

The Cerrado is a hot sub-humid tropical climate and distinct wet and dry seasons, the area consists of tropical forests, grasslands and savannah whose acidic soils are relatively infertile (Rada, 2013). The region is second to the Amazon in its contribution to land use change and forestry emissions in Brazil (Table 1.1).

Although the Cerrado accounts for around 37% of beef production in Brazil, it has been estimated that 50% to 80% of the approximately 60 Mha of pastures in the Cerrado are degraded, with loss of soil fertility and decrease in biomes (Peron and Evangelista, 2004). Thus, the adoption of pasture better management would reverse soil carbon loss (Mercedes M. C. Bustamante et al., 2012). Around 90% of Cerrado grasses are the African origin, *Brachiaria* spp. (Sano et al., 2010). Those species are extremely well adapted to the Cerrado's low-fertility acidic soils (Braz et al., 2013).

Since the recent success in reducing deforestation in the Amazon (Nepstad et al., 2014a), the Cerrado biome took over as the biome with highest deforestation rates in Brazil and dominates the land use change (LUC) sector emissions (MCTI, 2014). In 2012, LUC emissions in the Cerrado and Amazon accounted for 109 Mega tonnes of CO_2 equivalent (Mt CO2e) and 33 Mt CO2e, respectively. In that year, the Cerrado accounted for 72.5% of national LUC emissions (MCTI, 2014). GHG emissions from cattle enteric fermentation (CH_4) and excreta emissions (N_2O) in the Cerrado corresponds to 68% of LUC emissions in that biome and 39% of total Brazilian herd emissions (Mercedes M. C. Bustamante et al., 2012).

Table 1.1:Beef production share and agriculture related emissions in the Brazilian biomes

Biome	Beef production share[2] (%)	Emissions[3] (Mt CO_2-e)	GHG emissions share (%)
Amazon	28.5	140	52
Cerrado	37	109	41
Atlantic Forest[1]	23.5	-5	-2
Caatinga		6	2
Pantanal	11	2	1
Pampa		16	6

[1] Negative emissions are due to CO_2 removal by forestry plantations

[2] (IBGE, 2015)

[3] (MCTI, 2014)

As the most important beef production system in Brazil, the Cerrado is also the biome with the greatest potential of soil organic carbon (SOC) removals through improved pasture management. Several studies show that improving tropical grasses productivity results in increased SOC stocks (Braz et al., 2013; Maia et al., 2009), with net atmospheric CO_2 removals of almost 1 Mega gram of C per hectare-year ($MgC.ha^{-1}yr^{-1}$) (Braz et al., 2013) when comparing degraded and improved pastures in the Cerrado.

1.4 Aims and objectives

The contribution of this thesis lies in the development of a policy-relevant LP model to illustrate scenarios corresponding to a key SAI challenge defined by Garnett et al. (2013).

Existing whole-farm and regional optimization models relating to grasslands typically consider fixed forage productivity within production systems (e.g., extensive, semi-extensive and intensive). In such models the changes on SOC stocks are not modelled as a function of pasture management. This thesis argues that this overly simplistic representation of production practices and failure to account for SOC provide a misleading picture of pasture based system productivity and GHG emissions.

This work addresses the SAI challenge in Brazil by using and improving the LP model, called Economic Analysis of Greenhouse Gases for Livestock Emissions (EAGGLE) (Oliveira Silva, 2013). EAGGLE is a detailed whole-farm model focused on the optimization of pasture restoration practices and represents a whole cycle (cow–calf, stocking and finishing) beef production farm consisting of five compartment, accounting for: (i) herd dynamics, (ii) financial resources, (iii) feed budgeting, (iv) land use: pasture recovery dynamics and crops, and (v) soil carbon stock dynamics. The model calculates GHG emissions using consequential LCA emissions factors for the farm activities.

In Chapter 2, a version of the EAGGLE model is used to evaluate the GHG mitigation potential and economic benefit of optimizing pasture management through the partitioning of initially uniform pasture area. Chapter 3 further develops the model to define abatement potential and cost-effectiveness of key mitigation measures applicable to the Brazilian Cerrado. Chapter 4 demonstrates the extent of cost-effective mitigation that can be delivered by the livestock sector on the Intended Nationally Determined Contributions (INDC), and to show a result that underpins the INDC target of zero deforestation. Chapter 5 evaluates the consequences of reducing (or increasing) beef production on GHGs in the Cerrado system. Chapter 6 presents conclusions.

Chapter 2 - Optimizing pasture restoration through improved restoration practices and rural credit

2.1 Abstract

Grassland degradation compromises the profitability of Brazilian livestock production, and pasture recovery is a promising strategy for sustainable intensification of agriculture (SAI). Recovery increases carbon sequestration into the soil and can potentially avoid deforestation; thereby reducing emissions intensity (EI), but only at increased investment cost per unit of area. We develop a multi-period linear programming (LP) model for grazing beef production planning to represent a typical *Cerrado* stocking and finishing beef farm. We compare economic and environmental performance of two alternative optimized pasture management approaches relative to the traditional practice (TRP), which is based on restoring pasture after a full degradation cycle of 8 years. The scenarios considered the difference made by access to subsidized credit through the Low Carbon Agriculture program ("Programa ABC"). The model estimates EI using upstream life cycle assessment (LCA), and dynamically estimates soil organic carbon (SOC) changes as a function of pasture management. The results show net present values (NPV) ranging from -67 Brazilian reals per hectare-year (R$.ha^{-1}yr^{-1}) to around 300 R$.ha^{-1}yr^{-1}, respectively for traditional and optimized pasture management strategies. Estimated EI of the TRP is 9.26 kg CO_2 equivalent per kg of carcass weight equivalent (kg CO_2e/kg CWE) relative to 3.59 kg CO_2e/kg CWE for optimized management. Highest emission abatement results from improved SOC sequestration, while access to credit could further reduce EI by around 20%. We consider the effects of alternative credit interest on both NPV and EI. The results provide evidence to inform the design of Brazil's key domestic policy incentive for low carbon agriculture, which is an important component of the country's Intended Nationally Determined Contributions (INDC) on emissions mitigation. The results also contribute to the global debate on the interpretation of SAI.

2.2 Introduction

Brazil is the world's second largest beef producer using systems that are predominantly pasture-based; i.e., around 90% of cattle are pasture-fed only (Anualpec, 2013). Despite this, more than half of pasture area are degraded to some extent (De Oliveira et al., 2004). Gouvello et al. (2011) estimated that increasing beef productivity could provide the land needed for the expansion of crops for food and biofuel production in a near-zero deforestation scenario, while meeting increasing beef demand, at least up to 2040. Such actions are likely to reduce GHG emissions by lowering methane per unit of product, by avoiding deforestation and increasing soil organic carbon stocks (Gouvello et al., 2011).

Despite observed productivity gains made over the last three decades (Martha et al., 2012), challenges remain to reverse the economic losses from grassland degradation, while accommodating growing demand and simultaneously avoiding the conversion of natural habits. At around 73.5 kg of CWE/ha^{-1}.yr^{-1} average Brazilian productivity is low relative to a potential of 294 kg CWE. ha^{-1}.yr^{-1} that could be reached if improved pasture management practices were adopted (Strassburg et al., 2014). Pastures can be restored by improving soil fertility and forage productivity by chemical and mechanical interventions. For example, improvements can be made by applying inputs (seeds, fertilizers) and through the use of machinery (e.g. mowing). As degradation advances, more drastic soil interventions are required to restore productivity.

Despite policy interest in reversing degradation, we note the absence of any farm-scale economic appraisals demonstrating the trade-offs between investments in pasture restoration and the environmental returns, resulting from the potential increased soil organic carbon stocks (SOC) from restored pastures. Such assessment would ideally consider the dynamics of pasture degradation and restoration, and the cost-effectiveness of different management options. Existing farm and regional optimization models typically consider fixed forage productivity within production systems (e.g., extensive, semi-extensive and intensive) (Britz and Witzke, 2012; Dent et al., 2013; Weintraub and Romero, 2006). In such models the changes on SOC stocks are not modelled as a function of pasture management. An overly simplistic representation of production practices and failure to account for SOC provide a misleading picture of system productivity and GHG emissions.

The need for investment to address the nexus of pasture degradation, low productivity and food security and emissions is recognised as a national policy priority in Brazil, with restoration encouraged through the creation of a government-funded bank credit line for low carbon agriculture, the *Agricultura de Baixo Carbono* (ABC) - Low Carbon Agriculture program (Mozzer, 2011). To date, this program has not been subject to any formal economic analysis considering the economic return to the adoption of restoration practices. The restoration issue is also of sufficient global prominence to have been central to Brazil's mitigation commitments under the United Nations Framework Convention on Climate

Change. At the 15th Conference of the Parties (COP15) in 2009, the country proposed a voluntary emissions reduction target of around 40% relative to baseline emissions by 2020 to be achieved by its Nationally Appropriate Mitigation Actions (NAMAs) (Mozzer, 2011). At COP21 (2015), the commitment was nominally converted into an Independently Determined National Contribution (INDC) (Brazil, 2015), which proposed a further mitigation target of 43% reduction by 2030 relative to 2005 emissions. Both NAMAs and INDCs focus on reduced deforestation in the Amazon and the *Cerrado*, and include respectively the restoration of 15 million hectares (M ha) of degraded pastures between 2010-2020, and a further 15 M ha from 2020-2030.

This paper details an improved representation of pasture dynamics and environmental interactions, using an optimization model coupled with a full life cycle assessment approach (LCA) for a typical stocking and finishing beef cattle operation in the *Cerrado* biome. The objectives are: (i) to compare farmer's economic and environmental returns from investments in improved pasture restoration relative to traditional (baseline) practices; (ii) to understand how access to the ABC credit line improves the returns on investment; and (iii) to perform a sensitivity analyses of ABC interest rates on key economic parameters and emissions intensities.

2.3 Methods

Overview

Three versions of a LP model were developed to compare the economic and environmental performance subject to rural credit incentives and initial farm degradation levels: from severely degraded pasture to completely restored. Each version represents a restoration practice on a typical grazing system in the Brazilian *Cerrado*; the traditional pasture management and two alternative optimized restoration approaches. The model simulates beef production for a fattening and finishing system, accounting for herd dynamics, financial resources, feed budgeting, pasture recovery dynamics, and soil carbon stocks.

Mathematical modelling of restoration practices

Pasture degradation can be defined as the gradual loss of vigour, productivity and natural capacity for recovery to sustain production and quality of grass required by animals, and to overcome the detrimental effects of insects, diseases and weeds (Macedo and Zimmer, 1993). Traditional pasture management involves limited use of restoration practices, meaning that 50% to 80% of the Amazon and *Cerrado* pastures are currently degraded to some extent (Macedo et al. 2014; Peron and Evangelista 2004). Grasslands are typically not managed with fertilizers or lime throughout the production period (Maia et al., 2009). Instead, restoration interventions can occur around every 5 to10 years (Maia et al., 2009). In this study, traditional pasture management is assumed as a cyclical intervention every 8 or 10 years of constant grazing use; i.e., when pasture and soil are visibly degraded and dry matter productivity reaches an ecosystem equilibrium level and stops degrading.

Based on the pasture degradation definition of Macedo and Zimmer (1993), the model imposes a deterministic decline in dry matter productivity (DMP) with time. DMP levels (in tonnes of dry matter per hectare year) are represented by *{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 transference 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. The traditional restoration practice (TRP) is equivalent to restoration only when *P10* or *P11* are reached.

In contrast this paper models other two optimized approaches: The Fractional Restoration Practice (FRP) and the Uniform Restoration Practice (URP). URP permits restoration of the whole pasture at any point during the degradation process, e.g., DMP level *P5* could be restored to *P4*, *P3*, *P2* or *P1* or maintained at *P5* instead of degrading to *P6* at any time. FRP extends URP and 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 even a fraction may degrade to *P6*. In this way, a given pasture area is then partitioned into sub-areas instead of a uniform area as is the case in TRP and URP. The annual average values of the DMP levels are presented in Table 2.6 (Data section)

Mathematical description

Model's overview

Pasture management is optimized using a multi-period linear programming model for grazing beef production planning, with an application to a representative stocking and finishing beef cattle operation in the *Cerrado*.

The model focuses on optimizing decisions for pasture management while maximizing profit subject to biological and financial constraints. Stocking rates and, therefore, total output depend on feed production from pasture and consumption patterns driven by herd dynamics. The model accounts for intra- and inter-annual variations of pasture productivity and represents the processes of pasture degradation and restoration to optimize decisions on restoration from an economic perspective. The model was implemented in AIMMS algebraic language (Bisschop, 2011), comprising approximately 7000 variables and 4300 constraints for a 20 year planning period, and was solved using the CPLEX solver (CPLEX, 2009).

Table 2.1: Symbols for indices and functions of sets used in the mathematical description of the model.

Symbol	Description	Range/Value
p, q	pasture level	{P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, P11 }
j, k	steer age cohort	{1, 2, ..., 10}
m	planning month	{1, 2, ..., Tm }
t	planning year	{1, 2, ..., Ty }

Table 2.2: Symbols for Decision Variables

Symbol	Description	Unit
G_m	Cash income in month m	R$
H_m	Cash outcome in month m	R$
F_m	Cash in month m	R$

V_t	Loan taken in year *t*	R$
PV_t	Installment of loan paid in year *t*	R$
$X_{m,k}$	Purchased steers of age cohort *k* in month *m*	head
$Y_{m,k}$	Stocked steers of age cohort *k* in month *m*	head
W_m	Transferred dry matter from month *m* to *m* + 1	kg
$Z_{t,p}$	Area of pasture *p* in year *t*	ha

Table 2.3: Symbols and Values for Model Parameters

Symbol	Description	Value	Unit
$dm_{p,o}$	Initial herbage mass (dry-matter) of pasture level *p*	4000	$kg.ha^{-1}$
$A_{p,o}$	Initial area of pasture level *p*	See section 2.4	ha
A	Total pasture area	600	ha
l_{cr}	Credit limit	1000000	R$
γ_{cr}	Amortization system parameter[1]	0.234	dimensionless
FC	Farm fixed costs	3.66	$US\$.ha^{-1}.mth^{-1}$
α_k	Dry matter intake of animal of steer age cohort *k*	Table 2.4	$kg.hd^{-1}.mth^{-1}$
$\eta_{q,p}$	Cost of restoration from pasture level *q* to level *p*	Table 2.4	$US\$.ha^{-1}$
λ_k	Cattle maintenance cost for age cohort *k*	Table 2.4	$US\$.hd^{-1}$
μ_k	Mortality rate of steer age cohort *k*	Table 2.4	dimensionless
π	Transaction cost of purchasing cattle	30	$US\$.hd^{-1}$
$\rho_{p,M}$	Productivity of pasture level p in calendar month *M*	Table 2.6	$kg.ha^{-1}.mth^{-1}$
σ_M	Fraction of herbage mass loss due to senescence	0.00014	dimensionless
θ_k	Selling price of steer age cohort *k*	Table 2.4	$US\$.hd^{-1}$
τ_M	Minimum herbage mass transference at month *M*	1000(drought) 2000(rainy)	$kg.ha^{-1}.mth^{-1}$

ξ	Fraction of herbage mass loss due to grazing animals (grazing efficiency)	0.6	dimensionless

[1] Amortization parameter was calculated using the formula $\gamma = ir\left(1 - \frac{1}{(1+ir)^{np}}\right)^{-1}$, where *ir* represents the ABC program interest rate (6% per annum) and *np* the number of payments. i.e., 5 parcels according to "ABC Recuperação" – ABC Pasture Recovery[1]. Multiplying γ_{cr} by the loan gives the value of instalments.

Pasture dynamics

The area of each level *p* in a given year *t* is represented by $Z_{t,p}$ and the level of productivity of a partition for each month *M* in *{Jan, Feb, Mar,..., Dec}* of the calendar is represented by $\rho_{p,M}$.

The degradation process is represented as the annual transition of pasture levels in $\Omega = \{P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,P11\}$. In the case of FRP the model is designed to allocate proportions of the area optimally by either (i) maintain productivity at the current level (i.e. keep a sub-area in the same level), and (ii) improve productivity to any other more productive level, or (iii) let it degrade. Accelerated degradation due to overgrazing was not considered since the model adjusts the stocking rate according to what the animals consume and the available dry matter. Let $RZ_{t,p,q}$ be the pasture area that is transferred from partition *p* to partition *q* in year *t*, so pasture inter-annual productivity dynamics are given by:

$$Z_{t,p} = Z_{t-1,p-1} + \sum_{q}(RZ_{t,q,p} - RZ_{t-1,p,q}) \quad \forall t \quad (2.1)$$

Where *p* and *q* indexes correspond to the order of elements in Ω; *q* is auxiliary index in the same set as *p*. The first term in the right hand side (RHS) of Eq.2.1 represents degradation. The second term in the RHS represents the restoration dynamics; the first term

[1] http://www.bndes.gov.br/apoio/abc.html

in the sum $\Sigma\, RZ_{t,q,p}$ represents the area transferred from all other partition to p and $\Sigma\, \Sigma\, RZ_{t-1,p,q}$ sums up the area that is removed from p (restored) to any more productive level q.

Since the grassland restored area $RZ_{t,p,q}$ comes from the available area $Z_{t-1,p}$, it is required that

$$\sum_{q} RZ_{t,q,p} \leq Z_{t-1,q} \quad \forall q,t \quad (2)$$

The pasture productivity level at the end of the planning period was constrained not to be less than its initial value:

$$\sum_{p} \rho_{p,M} Z_{T_y+1,p} \geq \sum_{p} \rho_{p,M} Z_{t,p} \quad t = T_y, M = \text{Jan} \quad (2.3)$$

At the beginning of production, it is necessary to initialize the pasture partitions, thus:

$$Z_{t,p} = A_{p,o} \quad t = 1, \forall p \quad (2.4)$$

Herd dynamics and stocking rates

The model represents animal growth by defining age cohorts *k* with fixed attributes (e.g. body weight and feed intake, see Table 2.4). Fattening is modelled as the transfer from age cohorts as follows:

$$Y_{m,k} = X_{m,k} + (1-\mu_{k-1})Y_{m-1,k-1} + \sum_{j}\prod_{i=1}^{j}(1-\mu_{k-i})^3 X_{m-3j,k-j} - \sum_{j}\prod_{i=1}^{j}(1-\mu_{k+1-i})^3 X_{m-3j,k-j+1} \quad (2.5)$$
$$k < 10, \quad j \in \{1,2,..\} \quad \forall m$$

The third term in the RHS transfers all the purchased animals from previous cohorts *{k-1, k-2, k-3,…}* to the current cohort *k*, in month *m*. The fourth term in the RHS is similar, but it represents the transference from age cohort *k* to the successive cohorts *{k+1, k+2,…}*. As each age cohort is three months, the mortality rate from one cohort to another is accumulated via a relation of three months (fourth term in the RHS).

In the case of *k*=10 (slaughter age cohort), the number of steers is simply given by:

$$Y_{m,k} = \sum_j \prod_{i=1}^{j} (1-\mu_{k-i})^3 X_{m-3j,k-j} \quad k=10,\ j \in \{1,2,..\} \qquad (2.6)$$

Stocking rates are limited by the amount of available forage. Letting W_m be the dry matter transferred from one month to the next.

$$(1+\xi)\sum_k \alpha_k Y_{m,k} + W_m \le dm_{p,o} A_{p,o} + \sum_k \rho_{p,M} Z_{t(m),p} \quad m=1 \qquad (2.7)$$

And:

$$(1+\xi)\sum_k \alpha_k Y_{m,k} + W_m \le \sum_k \rho_{p,M} Z_{t(m),p} + (1-\sigma_{M(m)}) W_{m-1} \quad 1 < m \le T_m \quad (2.8)$$

Not all above-ground pasture biomass can be consumed by grazing animals, i.e., there is a minimum value of forage per area that will have to be transferred to the following month:

$$W_m \ge \tau_{M(m)} A \quad \forall m \quad (2.9)$$

Revenue flow

Income (G_m) is generated either from steers sold for slaughter or from bank credit lines.

$$G_m = \theta_{10} Y_{m,10} \quad \forall m \quad (2.10)$$

Expenses (H_m) is composed of farm fixed maintenance costs, cattle maintenance costs, purchasing cattle and investments on pasture restoration. Thus

$$H_m = FC * A + \sum_{k=1}^{8} (\pi + \theta_k) X_{m,k} + \sum_k \lambda_k Y_{m,k} + PI_m \sum_p \sum_q \eta_{p,q} RZ_{t(m),p,q} \quad \forall m \quad (2.11)$$

Where PI_m is a parameter vector used to discount the annual investments in pasture restoration in the selected month and PI_m is equal to 1 if m a payment month, or 0 if m is not a payment month.

At the first month of the planning period, cash flow is given by:

$$F_m = V_{t(m)} + G_m - H_m \quad m = 1 \quad (2.12)$$

And the credit lines must meet the credit limit:

$$V_{t(m)} \leq l_{cr} \quad \forall t \quad (2.13)$$

The credit line in Eq. 2.12 (variable V_t) is paid in 5 instalments (PV_t) after the 3rd year of contract:

$$PV_t = \sum \gamma_{cr} V_{t-(3+i-1)} \quad \forall t \quad (2.14)$$

Along the planning period, cash flow is given by:

$$F_m = (1-i) F_{m-1} + TI_m \sum_{cr} V_{t(m),cr} - PI_m \sum_{cr} V_{t(m)} + G_m - H_m \quad 1 < m < T_m \quad (2.15)$$

Similarly to TI_m, PI_m is used to set the months in which credit payments occur according to the number of instalments. A discount rate of 6% per annum (0.5% per month) applied to represent the opportunity cost.

At the end of the planning period, all steers are sold. Furthermore the farm has to pay costs of pasture post-production, i.e., pasture restoration investments necessary to let farm productivity be greater than or equal to the value of the initial year.

$$F_m = (1-i)F_{m-1} - G_m + H_m - \sum_k \theta_k Y_{m,k} + \sum_p \sum_q \eta_{p,q} RZ_{t(m)+1,p,q} \quad m = T_m \quad (2.16)$$

The objective function is to maximize the final cash:

$$Max \quad F_{T_m} \quad (2.17)$$

GHG emissions and SOC stocks

The model estimates GHG using emissions factors for activities within the notional farm gate. Emissions 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 direct emissions from N fertilization; and (d) CO_2 from changes in SOC stocks. Items (a) and (b) depend on herd composition: each age cohort has an associated emission factor of CH_4 and N_2O calculated using Tier 2 methodology (Eggleston et al., 2006) and equation 2.18.

$$ce_m = \sum_k (21 * \mathrm{CH4}_k + 310 * \mathrm{N2O}_k) Y_{m,k}, \ \forall m \quad (2.18)$$

Eq. 2.18 accounts for emissions converted to carbon dioxide equivalent (CO_2-e) for each cattle age cohort *k*, where ce_m is total cattle emissions in month *m*; $CH4_k$ *and* $N2O_k$ *are* the emissions factors for CH_4 and N_2O (in $kg.hd^{-1}.mth^{-1}$) for steers of age cohort *k* (Table 2.4), 21 and 310 are respectively the CH_4 and N_2O equivalence in CO_2e - in global warming potential for 100 years (GWP-100).

Due to the lack of studies in Brazilian conditions, for (c), we used the Intergovernmental Panel on Climate Change - IPCC Tier 1 default factor of 1% (Eggleston et al., 2006) as follows:

$$fe_t = 310 * cv_{N \rightarrow N_2O} \sum_p \sum_q NA_{p,q} RZ_{t(m),p,q} \quad (2.19)$$

Eq. 2.19 accounts for the emissions from N based fertilizers in year t (fe_t). The term inside the sum gives the amount of N applied for all pasture restoration options. The factor $cv_{N \rightarrow N2O}$ corresponds to the proportion of N converted into N_2O.

For (d), the emissions are calculated by modelling SOC dynamics. The model works with equilibrium values of the C stock for each pasture type (Table 2.6). The equilibrium values and equilibrium time horizon were calculated exogenously, using simulations from the CENTURY model (Parton et al., 1987) applied to *Cerrado* biophysical characteristics and using the annual dry mater productivity calculated for each pasture DMP level.

Detailed derivation of the soil organic carbon model developed in this analysis is presented below.

Based on equilibrium values and parameter that represents bioclimatic conditions, the model dynamically simulates SOC accumulation sensitive to pasture management. We first develop a version of SOC stock for a fixed DMP level p over time, then we generalise to a heterogeneous pasture area by calculating weighted average values.

Let $c_{t,p}$ be the SOC stock of pasture p in year t (in tonnes per hectare), the changes in SOC stocks over time (dc_t/dt) can be represented as function of an annual carbon input flux through photosynthesis (I_t), and the respiratory losses due to decomposer organisms (r_t), where r_t is proportional to the amount of SOC in t, i.e., $r_t = \rho c_t$; and ρ is the fraction of SOC which is lost by plant respiration, as proposed by Vuichard et al. (2007):

$$\frac{dc_{t,p}}{dt} = i_{t,p} - r_{t,p} \quad (2.20)$$

Assuming i_t=F fixed and nothing that respiration losses are proportional to C_t:

$$\frac{dc_{t,p}}{dt} = F - \rho_j c_{t,p} \quad (2.21)$$

At steady state dc_t/dt =0:

$$\frac{dc_{t,p}}{dt} = 0 \Rightarrow c^*_{t,p} = \frac{F}{\rho} = \varepsilon_j \quad (2.22)$$

Where $C^*_{t,p}$ = ε_p is the SOC of pasture p at equilibrium. Thus (2.21) can be written as:

$$\frac{dc_{t,p}}{dt} = \rho_p(\varepsilon_p - c_{t,p}) \quad (2.23)$$

Writing as difference equations (discrete-time analogue):

$$\Delta c_{t,p} = \rho_p(\varepsilon_p - c_{t-1,p}) \quad (2.24)$$

Thus, SOC accumulation is given by:

$$c_{t,p} = c_{t-1,p} + \rho_p(\varepsilon_p - c_{t-1,p}) \quad (2.25)$$

Given the equilibrium values of each pasture DMP level (ε_p), carbon respiration losses (ρ_p) and initial SOC stock ($c_{0,p}$), equation (2.25) estimates SOC at any time t. The parameter ρ_p can be calibrated to adjust an assumed equilibrium time, or obtained exogenously, e.g., by calibrating against the CENTURY model (Parton et al., 1987).

The parameter ρ_p is fixed across the pasture levels in $\Omega=\{P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,P11\}$, since Ω represents productivity levels of the same pasture species and bioclimatic conditions. Given ρ_p fixed, we show that the SOC under a heterogeneous pasture area composed of pastures p in Ω is equivalent to the weighted average of the individual areas of pastures p ($Z_{t,p}$) and SOC of pastures p ($c_{t,p}$). Let $w_{t,p} = \frac{Z_{t,p}}{\sum_p Z_{t,p}}$ represent the fraction of pasture p in the total area; and $c^H{}_t$ represents the total SOC accumulated in the total pasture area. Then:

$$c^H{}_t = \sum_p w_{t,p} c_{t,p} \quad (2.26)$$

Applying (2.25) in (2.26):

$$c^H{}_t = \sum_p w_{t,p} c_{t-1,p} + \rho\left(\sum_p w_{t,p}\varepsilon_p - \sum_p w_{t,p} c_{t-1,p}\right) \quad (2.27)$$

Substituting (2.26) into (2.27):

$$c^H{}_t = c^H{}_{t-1} + \rho\left(\sum_p w_{t,p}\varepsilon_p - c^H{}_{t-1}\right) = c^H{}_{t-1} + \rho\left(\varepsilon^H - C^H{}_{t-1}\right) \quad (2.28)$$

Since the total area is fixed ($\sum_p Z_{t,p} = A$), Eqs. 2.26-2.28 are linear relations.

Below we present the proof that summing the individual SOC variations $\Delta c_{t,p}$ of a pasture area composed of sub-areas of pastures with different dry matter productivity (DMP) levels is equivalent to calculating the weighted average between the individual areas of pastures p ($Z_{t,p}$) and SOC of pastures p ($c_{t,p}$). This is equivalent to proving the relation (29).

$$\Delta c^{H}{}_{t} = \sum_{p} \Delta c_{t,p} \quad \forall t \quad (2.29)$$

From (2.27):

$$\Delta c^{H}{}_{t} = \rho \left(\sum_{p} w_{t,p} \varepsilon_{p} - \sum_{p} w_{t,p} c_{t-1,p} \right) \quad (2.30)$$

Imposing that $w_{t,p}(\varepsilon_q - c_{t-1,q}) = 0$ if $p \neq q$, (2.30) can be rearranged as:

$$\Delta c^{H}{}_{t} = \rho \sum_{p} w_{t,p} \sum_{p} \left(\varepsilon_{p} - c_{t-1,p} \right) \quad (2.31)$$

Since $\sum_{p} w_{t,p} = 1 \quad (2.32)$

$$\Delta c^{H}{}_{t} = \rho \sum_{p} \left(\varepsilon_{p} - c_{t-1,p} \right) = \sum_{p} \Delta c_{t,p} \qquad (2.33)$$

Item (f), the LCA emissions associated with inputs and farm operations applied in the farm are calculated according to:

$$le_{t} = \sum_{inp} lca_{inp} \sum_{p} \sum_{q} INA_{inp,p,q} RZ_{t,p,q} \quad (2.34)$$

Eq. 2.34 gives the annual LCA emissions of (f) by accounting for the total application of a given input (or farm operation) *inp* in year *t* (term inside the double sum) and multiplying it by the input LCA emission factor, and then summing over *inp*. Where lca_{inp} represents the emission factor of input *inp*; $INA_{p,q}$ the amount of applied input *inp* associated with pasture restoration from pasture *p* to *q* (variable $RZ_{t,p,q}$).

Data

The typical system represented is a 600 ha grazing beef cattle farm in the city of *Campo Grande* (20.4683° S, 54.6225° W) in the state of *Mato Grosso do Sul*, Brazil, which was taken as a reference for climate and bio-economic data. The analysis used a planning period of 20 years and a budget limited to retained capital or the ABC credit line. The aim is to fatten, finish and sell *Nellore* steers with diet based solely on forage from pasture *Brachiaria brizantha cv. Marandu*.

Direct cattle CH_4 emissions (Table 2.4) were calculated using Tier 2 methodology (Eggleston et al., 2006). Direct N_2O emissions from manure were estimated using a modified IPCC Tier 2 method. This follows recommendations in previous studies, e.g. Lessa et al. (2014) suggesting that urine and faeces have significantly different emissions factors under typical low protein content diets in Brazil, and that under such conditions, N excretion can be higher in faeces than urine (Xavier et al., 2014). Lessa et al., (2014) estimated N excretion separately for urine and faeces with respective emission factors derived from Brazilian studies (Cardoso et al., 2016).

Table 2.4: Steer Bioeconomic Data

Age cohort	Age (months)	Mortality[a] (%.mth^{-1})	Avg SBW[b] (kg.hd^{-1})	DMI[c] (kg.mth^{-1})	Price[d] (R$.hd^{-1})	Maintenance Cost[e] (R$.hd^{-1}.mth^{-1})	CH_4[f], kg.head.$^{-1}$.mth^{-1}	N_2O[g], kg.head.$^{-1}$.mth^{-1}
1	[6,9)	0.42	189	144.9	658	1.74	3.35	0.013
2	[9,12)	0.42	222	166.2	691	1.95	3.78	0.015
3	[12,15)	0.2	255	187.2	802	2.19	4.19	0.017
4	[15,18)	0.2	289	208.8	913	2.4	4.6	0.018
5	[18,21)	0.2	322	229.8	1,044	2.61	4.99	0.020
6	[21,24)	0.2	355	251.1	1,158	2.82	5.37	0.021
7	[24,27)	0.03	388	272.4	1,271	3.06	5.74	0.023
8	[27,30)	0.03	421	294	1,411	3.27	6.1	0.024

9	[30,33)	0.03	454	315.9	1,526	3.48	6.46	0.026
10	[33,36)	0.03	490	339.9	1,278	3.72	6.84	0.027

[a] Cited in Arruda and Corrêa (1992)

[b] Average shrunk body weight (Avg SBW) as proposed by Costa et al. (2005)

[c] Dry matter intake (DMI) as cited in National Research Council (NRC 2000)

[d] Prices were based on time series collected from the Institute of Applied Economics (IEA, 2012) and were deflated to 2012 values using Fundação Getúlio Vargas (FGV 2012). Brazilian reals (R$) are expressed in 2012 values (1 R$-2012 is equivalent to 0.49 US$-2012).

[e] Proposed by Costa et al. (2005)

[f,g] Details of parameters used for emissions factor calculation are described in Table 2.5.

Table 2.5: Parameters for emissions factors estimation

Parameter*	Units	Value	Reference
Methane conversion factor (Ym)	%, Gross Energy	0.065	Eggleston et al. (2006)
Crude protein (CP) wet season	%, feed dry matter	0.09	This study
CP dry season	%, feed dry matter	0.065	This study
Average live weight gain (LWG)	kg/day	0.36	This study
Diet Digestibility	%, feed dry matter	0.58	This study
Feces emission factor (EF) wet season	%, N Excretion	0.0014	Cardoso et al. (2016)
Feces EF dry season	%, N Excretion	0	Cardoso et al. (2016)
Urine EF wet season	%, N Excretion	0.0193	Cardoso et al. (2016)
Urine EF dry season	%, N Excretion	0.0001	Cardoso et al. (2016)
Dry season duration	%, Year	0.574	Cardoso et al. (2016)
N excreted in urine wet season	%, N Excretion	0.426079	Estimated according to Cardoso et. al. (2016)
N excreted in urine dry season	%, N Excretion	0.189233	Estimated according to Cardoso et. al. (2016)
N concentration in LWG	%, Mass	0.025	Cardoso et al. (2016)
N volatilisation and re-deposition (EF4)	kg N_2O-N/kg N volatilized	0.010	Eggleston et al. (2006)
N leaching/runoff (EF5)	kg N_2O-N/kg N in leaching and runoff	0.0075	Eggleston et al. (2006)

*For the remaining IPCC tier 2 parameters, default values were used.

Pasture productivity (Table 2.6) for each level in *Ω = {P1,P2,P3,P4,P5,P6,P7,P8, P9,P10,P11}* was estimated using the Invernada software (Barioni, 2011), which uses monthly averages of historical climate data and the amount of nitrogen (N) applied to estimate forage potential accumulation rates, according to the model of (Tonato et al., 2010) for the main grass species used in Brazil.

Table 2.6: Pastures Accumulation Rates and Equilibrium C Stock Values in Function of Pasture Type (Brachiaria brizantha cv. Marandu)

Pasture	DM[a] ($t.ha^{-1}.yr^{-1}$)	Soil carbon stock equilibrium[b] ($t.ha^{-1}$)
P1	19.6	84.3
P2	18.6	83.5
P3	17.6	82.7
P4	15.1	72.5
P5	12.6	62.3
P6	10.7	53.8
P7	8.7	45.2
P8	7.3	38.8
P9	5.8	32.4
P10	4.9	29.3
P11	3.9	26.1

[a] From to Tonato et al. (2010)

[b] Estimated for 20cm depth (Parton et al., 1987).

The restoration costs (in R$-2012 per hectare) in Table 2.7 (the values of $\eta_{p,q}$) were calculated as a function of the individual application of inputs and services employed in restoration practices. We assume the cost of restoring pasture from p to q, where p and q can be any element in Ω is given by the cost of inputs/machinery used to maintain pasture p (because the restoration decision is made at the moment of degradation) plus the cost required to restore one hectare from degraded level *P11* to q, less the cost of inputs to restore one hectare from level *P11* to p, but only positive differences in the amount of inputs/services are accounted for. Let *inp* represent any input or service and $ap_{inp,F,q}$ be the amount of inputs/machinery required to restore one hectare of pasture level *P11* to level q. Then $\eta_{p,q}$ is given by:

$$\eta_{p,q} = \sum_{inp} c_{inp}(ap_{in,p,p} + ap_{inp,F,q} + ap_{inp,F,p}) \quad (20)$$

Table 2.7: Cost of Pasture Restoration Management Optimization[a].

$\eta_{p,q}$ (R$.ha^{-1})											
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
P1	267.0										
P2	364.8	222.0									
P3	462.6	319.8	177.0								
P4	525.2	382.4	239.6	106.5							
P5	587.8	445.0	302.2	169.0	35.9						
P6	767.1	624.3	481.5	348.4	215.2	29.2					
P7	946.4	803.6	660.8	527.7	394.6	208.5	22.4				
P8	1055.9	913.1	770.3	637.2	504.0	318.0	131.9	18.1			
P9	1165.4	1022.6	879.7	746.6	613.5	427.4	241.4	127.6	13.8		
P10	1204.2	1061.4	918.6	785.5	652.4	466.3	280.2	166.4	52.6	6.9	
P11	1243.1	1100.3	957.5	824.4	691.2	505.2	319.1	205.3	91.5	45.7	0.0

[a] Details of inputs (e.g., nitrogen, seeds, limestone, micro-nutrients) application for each level in Ω are described in De Oliveira Silva et al. (2015).

We assume the farm has fixed costs proportional to pasture area. Fixed costs are associated with expenses for cattle (veterinarian equipment), labour and infrastructure and taxes for a beef production system in the state of *Mato Grosso do Sul*.

Table 2.8: Farm Annual Maintenance Costs[a].

Farm structure variable	Cost (R$2012.ha^{-1})
Working animals, horse	
Depreciation	0.2
Interest	0.1
Machinery and equipment	
Depreciation	11.6
Interest	4.0
Veterinary equipment	
Depreciation	0.2
Telephone device	
Depreciation	0.1
Farmer minimum living expenses	0.9
Maintenance of machinery and equipment	9.9
Services and labor	11.9
Fuel and lubricant	4.0
Taxes and fees	1.2
Total farm costs	43.9

[a] Costs as proposed by Costa et al. (2005) cost structure.

To start production, the farmer is allowed to take a loan (variable $V_{t,cr}$) in the first year from the ABC program if adopting one of the ABC greenhouse gas mitigation measures (Mozzer, 2011), such as pasture restoration. The credit conditions for cattle breeders investing in pasture restoration are a limit of 1 million Brazilian reals (R$) and the payment can be made in 5 instalments with a 3 year grace period and an interest rate of 6% per annum (http://www.bndes.gov.br/apoio/abc.html).

Farm initial state scenarios

The quality of the pastures (or the level of degradation) at year zero of the planning period, i.e., before the production starts, is an important factor when assessing the effectiveness of restoration practices. Three initial farm degradation scenarios are assumed: the Low Pasture Productivity (LPP), with initial pasture area the whole pasture at *P7* (8.7 t DM.ha^{-1}.yr^{-1}); the Intermediate Pasture Productivity (IPP), with initial pasture area at level *P5*

(12.6 t DM.ha^{-1}.yr^{-1}); and the High Pasture Productivity (HPP), with initial pasture area at level *P1* (19.6 t DM.ha^{-1}.yr^{-1}). We compare the traditional pasture management with the proposed optimized restoration practices with initial investments subjected to available capital with and without government subsidies for intensification, i.e., access to ABC credit.

Shadow price of carbon

A carbon value is not included in the optimization model because there is currently no carbon market entry points for this mitigation effort. However, the methodology allows the implicit calculation of a carbon value. The restoration practices comparison assumes no emissions limit, but we use an emission limit E_{BAU}, corresponding to the total emissions of the unconstrained solution, to calculate the shadow price (of carbon) implied by this emissions constraint (Eq. 36). We also constrain the model to produce the same beef output as in the unconstrained solution. Ae shadow price is estimated as the change in the objective function from relaxing the emission constraint by one tonne of CO_2e in relation to the total emissions of the unconstrained solution.

$$\sum_t ce_t + \sum_t \Delta c^H{}_t + \sum_t fe_t + \sum_t le_t \leq E_{BAU} \qquad (2.36)$$

Where the terms in the left hand side are respectively emissions from cattle, SOC, fertilizers, the use of inputs and farm operations.

2.4 Results

NPV for TRP ranges from -67 R\$.ha^{-1}yr^{-1} to 53.5 R\$.ha^{-1}yr^{-1}, depending on the initial degradation level and access to ABC credit. A negative NPV arising as a result of grassland degradation is actually observed for some beef stocking and finishing systems in *Mato Grosso do Sul* (Crespoline dos Santos, 2015).

The results indicate that investing in beef production is highly sensitive to the initial level of degradation if TRP is adopted. The LPP scenario implies a negative NPV of -67R$.ha.$^{-1}$.yr^{-1} (Fig. 1A, LPP). Under LPP access to ABC credit does not alter the optimum farm decisions since no credit is taken if decisions are based on profit maximization. This is because revenues generated in the first years are insufficient to repay the loan instalments and to cover farm costs, i.e., first payment of five, after three years of credit uptake, as it was modelled in line to ABC credit contract policies (See *farm costs* section). Instead by using their own capital, payment is made at the end of production, i.e., at the end of 20th year of production.

Under IPP and HPP, the TRP NPV is sensitive to credit access. The NPV of 10.2 R$.ha^{-1}.yr^{-1} is around 4 times greater than production without access to ABC (Fig 2.1A, IPP).

In contrast to TRP, optimizing pasture restoration though FRP or URP reduces the importance of the initial degradation level; NPV of 273.4 R$.ha^{-1}.yr^{-1} and 274.5 R$.ha^{-1}.yr^{-1}, respectively for LPP and HPP initial productivity scenarios (without ABC credit). As expected, the annual average stocking rates are also less dependent on initial productivity. The reason is that taking the alternative restoration practices leads to optimal stocking rates more efficiently, with minimum costs and less time required. The average stocking rates were around 1.6 animal units per hectare (AU.ha^{-1})[2], which accords with carrying capacity suggested by Strassburg et al. (2014).

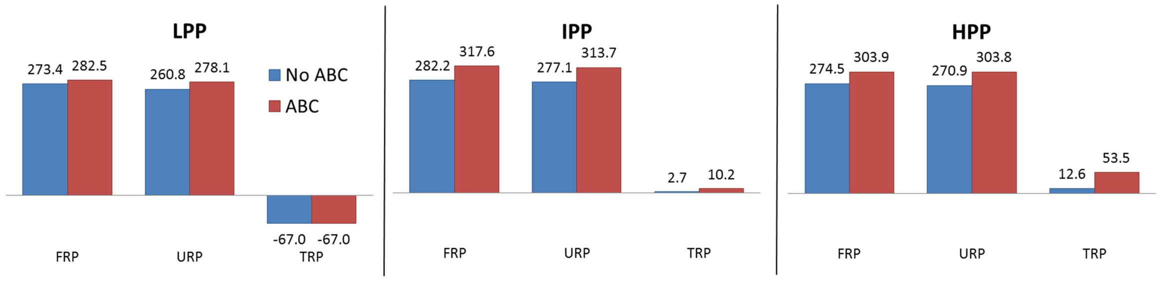
ABC credit promotes profitable and sustainable production only when combined with appropriate pasture management. Taking the ABC credit could increase NPV from 2.7 R$.ha^{-1}.yr^{-1} to 10.2 R$.ha^{-1}.yr^{-1}, when compared to no access for TRP (Fig. 2.1A).

Figure 2.1C shows that FRP could require less investment in restoration than TRP; e.g., investments are 62,700 R$ and 69,800 R$ per year, respectively for the FRP and the TRP under LPP (no ABC), while the average restoration area is around 3 times greater for the FRP than TRP (Figure 2.1D).

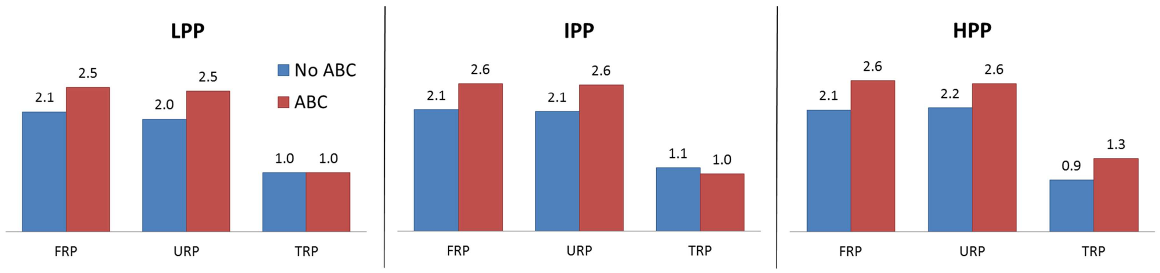
Although the credit promotes more investment per year in restoration, Figure 2.1D shows less area is restored per year when the credit is available. Because ABC increases cash incomes, more intensive restoration options are undertaken, reducing the average restoration area but improving forage productivity.

[2] In Brazil an animal unit (AU) is equivalent to 450 kg of live weight.

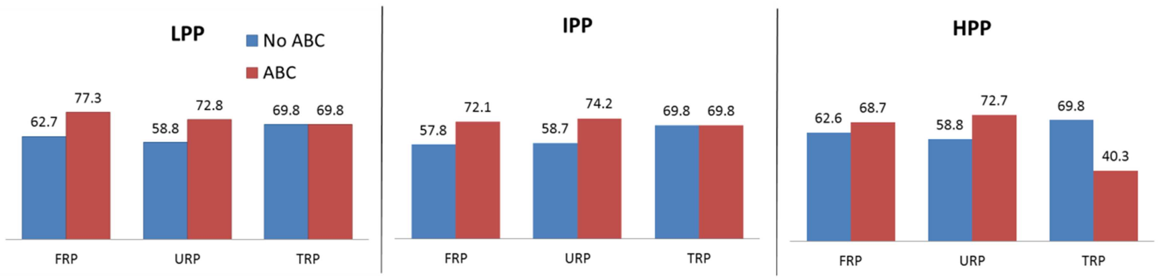
Figure 2.1E shows that the TRP beef productivity ranges from 96 to 104.7 kg CWE.ha^{-1}.yr^{-1} (without ABC) and 167.6 kg CWE. ha^{-1}.yr^{-1} (with ABC). Optimizing pasture restoration could double or triple beef productivity if combined with the ABC credit (Fig. 2.1E).



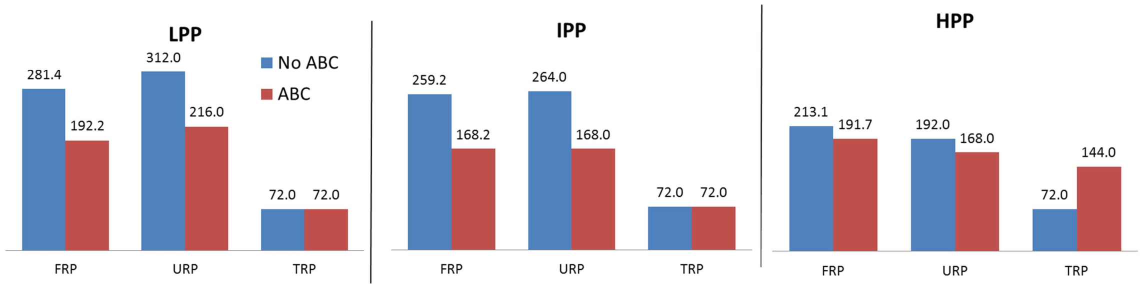
(b) Stoking rates (head.ha^{-1})



(c) Average restoration investments (10^3 R$.yr^{-1})



(d) Average pasture restoration (ha.yr^{-1})



(e) Average beef productivity (kg CWE.ha^{-1}.yr^{-1})

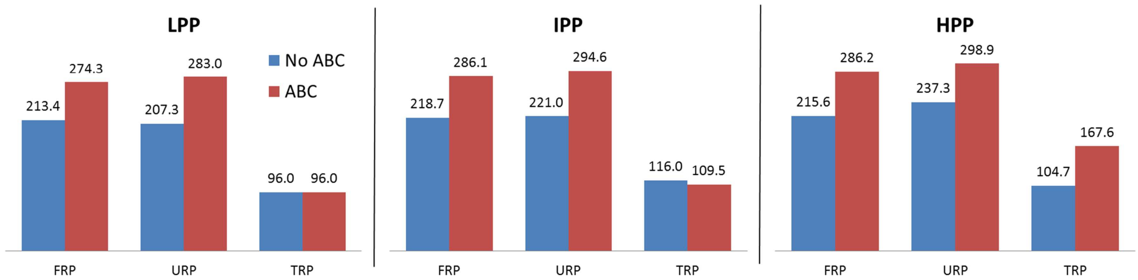
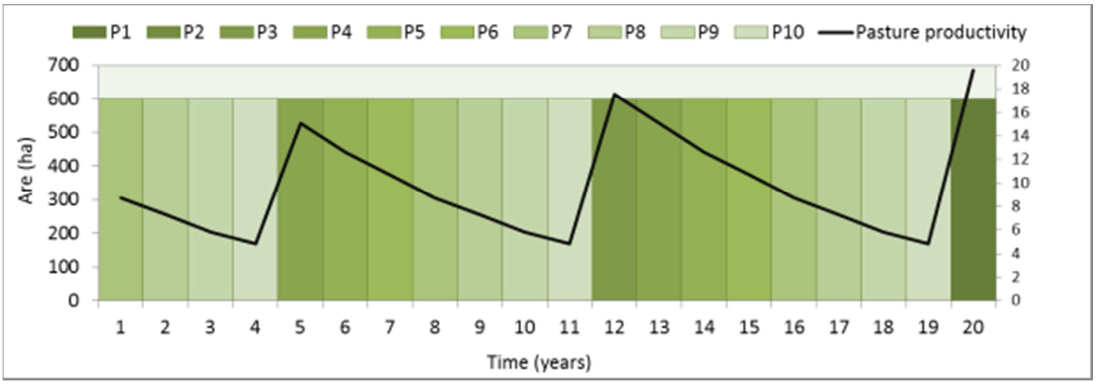


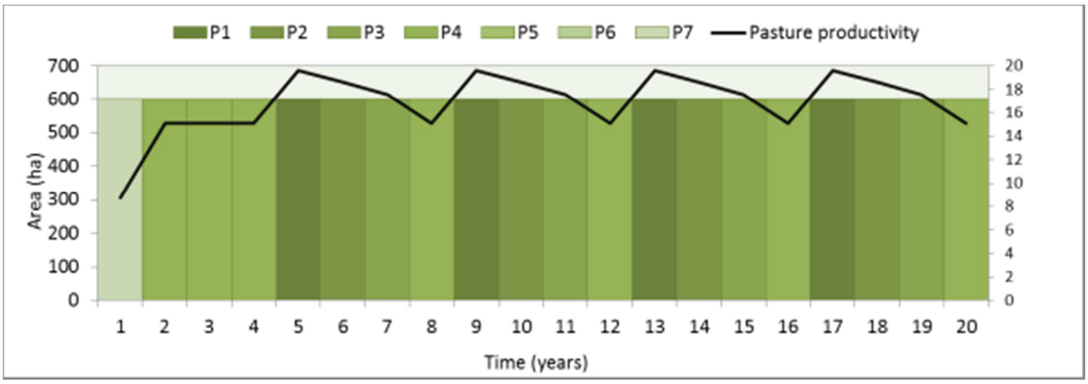
Figure 2.1: Comparison of economic returns depending on initial degradation scenarios (LPP, IPP, and HPP) and access to ABC credit.

Figures 2.2A-C provide graphical representation of the pasture management practices, i.e., pasture composition in terms of pasture types defined in Table 2.6, and the associated forage productivity in tonnes of dry matter per hectare per year (t DM.ha^{-1}.yr^{-1}), under the LPP scenario.

(a)



(b)



(c)

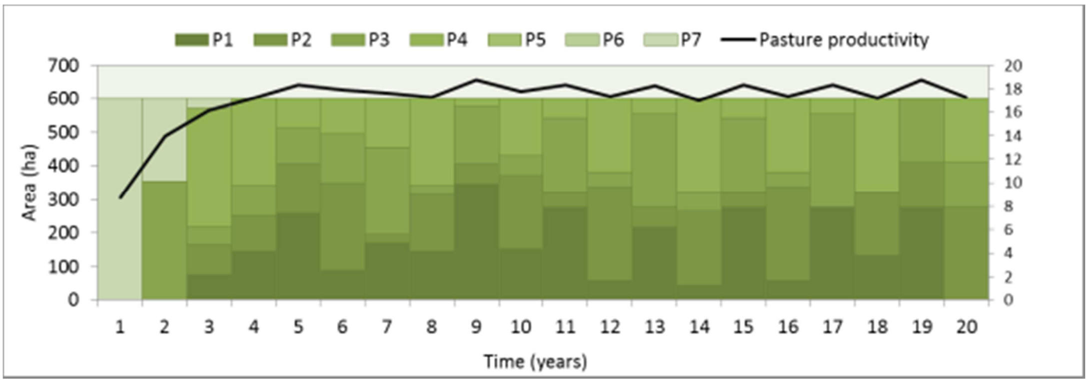


Figure 2.2: Pasture composition and associated forage productivity (a) TRP; (b) URP; and (c) FRP restoration practices under the LPP scenario.

Figure 2.2A-C shows that FRP has more consistent productivity, i.e., allowing for optimal relation between forage productivity and stocking rates over the production time.

Fractionating pastures also require less cash inflow for investments, a barrier for promoting the adoption of sustainable intensification measures (de Oliveira Silva et al., 2015a; Moran et al., 2013)

In both FRP and URP the optimum level of productivity is around 18.3 t DM.ha^{-1}.yr^{-1}.Pasture degradation and restoration dynamics can cause SOC to switch from a sink to a source of CO_2 (Smith, 2014). Figure 2.3 shows TRP oscillates between losses or gains in SOC stocks, resulting in a slight increase from 45.2 to 47.2 tonnes of carbon per hectare (t-C.ha^{-1}), while SOC increased from 45.2 to 60.5 t-C.ha^{-1} for URP and FRP.

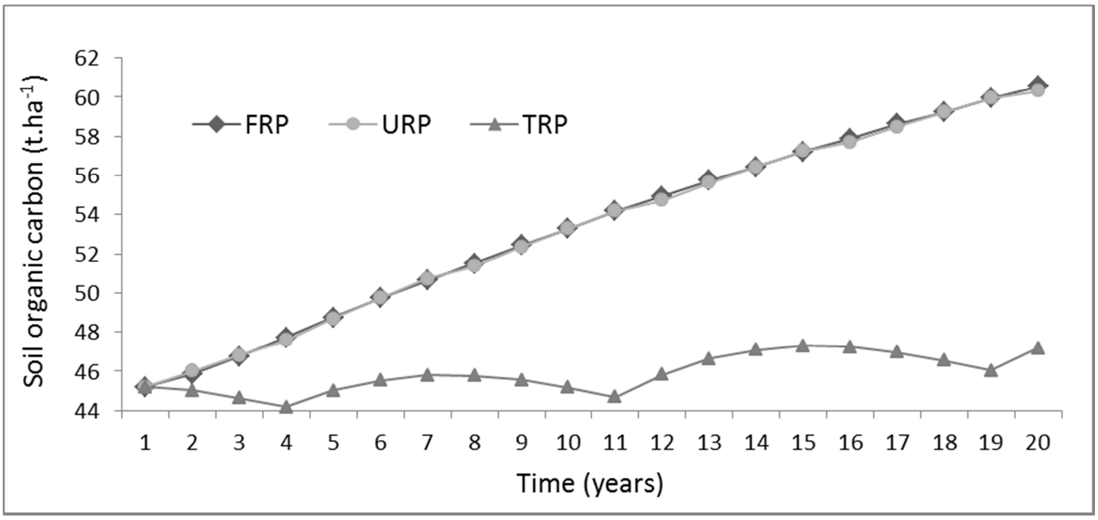


Figure 2.3: soil organic carbon stocks as a function of time and restoration practices.

We use the LPP scenario to compare the life cycle assessment emissions intensity of the alternative pasture management practices. The results show that SOC plays a major role in reducing both the absolute total, and emissions per kilogram, while LCA associated with the use of farm inputs, e.g., nitrogen, seed distribution, internal transport, are of minor importance - in relation to direct cattle emissions and SOC. Optimizing pasture management though FRP could double production from 96.0 kg of carcass-weight equivalent per hectare year (kg-CWE.ha^{-1}.yr^{-1}) to 213.4 kg of CWE. ha^{-1}.yr^{-1} while decreasing the TRP emissions of 494.34 tonnes of CO_2e per year (tCO_2-e.yr^{-1}) by 30%. Optimizing through URP could increase production to 207.4 kg of CWE ha^{-1}.yr^{-1} while reducing average annual emissions by 45%.

Figure 2.4 shows EI as an aggregation of the main GHG emissions sources from the stocking and finishing beef systems, i.e. excluded purchased calves related emissions. Emissions intensities were calculated with and without access to ABC credit under the LPP scenario. Due to the high initial level of degradation in the LPP scenario, even the TRP restoration means pastures are (moderately) intensified during the production period. Estimated EI is 9.26 kg CO_2-e/kg CWE.

Figure 2.4 shows that adopting the optimized pasture management practices could reduce these to around 3.59 kg CO_2-e/kg CWE, with emissions abatement resulting from SOC sequestration from improved grasses. Note that direct cattle emissions account for around 11.87 kg CO_2-e/kg CWE, whereas SOC sequestration abates 3.8 kgCO_2-e/kg CWE, or 30% of cattle EI under TRP. If FRP or URP is adopted, gains in SOC stocks could abate 80-85% of cattle direct emissions (CH_4 and N_2O).

(a) (b)

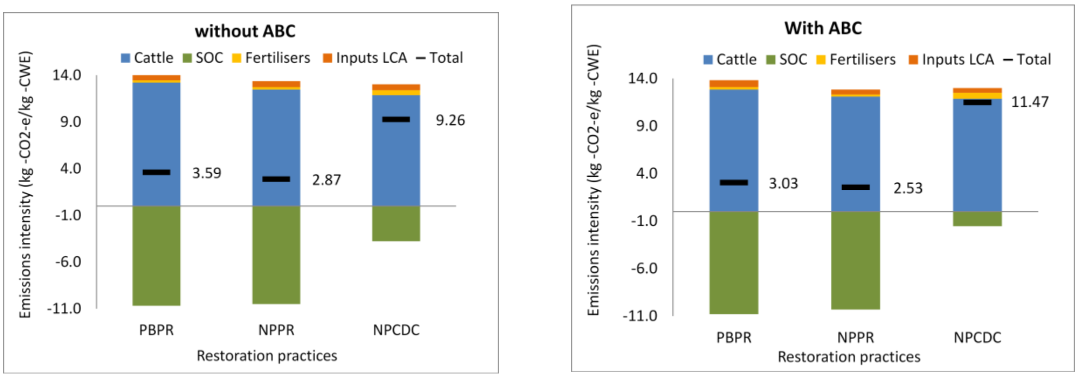
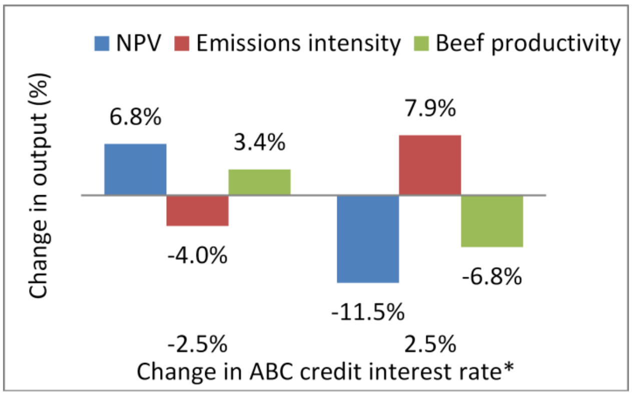


Figure 2.4: Emissions intensity comparison for the restoration practices under the LPP scenario without ABC credit (a) and with ABC credit (b). Emissions from cow-calf phase are not included.

On average, access to ABC credit reduces EI by around 20% when compared to the same pasture management practice, assuming that producers risk investing their own capital to optimally manage pastures in the scenario without ABC credit. This is because ABC credit provides more incentive for intensification (as seen in Fig. 2.1C-D), and SOC stocks are higher than without the credit.

Average annual emissions for the FRP is 473.2 tonnes of CO_2e per year (t $CO_2e.yr^{-1}$). The shadow price analysis suggests a value of 30.8 R$ per tonne of abated CO_2e (or 15.1 US$). This can be interpreted as the minimum value farmers would have to be paid per tonne of CO_2e to maintain profitability as shown in the objective function.

Figure 2.5 shows a sensitivity analysis of ABC interest rates against NPV, emissions intensity and beef productivity for FRP.



* Change in relation to ABC baseline interest rate (5.5% per annum).

Figure 2.5: Sensitivity analysis of ABC credit interest rate versus net present value, emissions intensity and beef productivity for FRP.

2.5. Discussion

Sustainable agricultural intensification rhetoric has highlighted the inherent multi-dimensional trade-offs in meeting increasing food demand by optimizing production while minimizing external costs. Existing literature is largely conceptual, e.g. Loos et al. (2014), and less specific about the relevant scale of analysis. Farm scale optimization is clearly necessary to demonstrate the economic feasibility of any transition from traditional production practices to intensified alternative pasture-based systems.

The farm level focus of this analysis means that we ultimately do not consider the extent to which systems intensification will influence deforestation rates through less extensive land use. Sparing land that could then be used for alternative production options clearly opens up the potential for other market mediated effects that could be just as extensive

(Cohn et al., 2014; Gouvello et al., 2011). SAI technologies alone are unlikely to reduce land expansion if unaccompanied by targeted land management incentives and effective deforestation control policies (Arima et al., 2014).

To date however, data on the full extent of pasture degradation in Brazil are patchy and this handicaps more accurate calculation of current average dry matter productivity and SOC stocks.

Our results inform the economics of the 30 M ha restoration target (2010-2030) defined in Brazil's by NAMAs/INDC commitments, and suggest significantly increased profitability and reduced emission through strategic partitioned pasture restoration. Note that this method could be realistically applied at farm level by fenced partition of pasture area and that the result holds without including any notional monetary value that might in future be associated with farm carbon credits. Note that there are currently no significant agricultural carbon credit schemes in Brazil. The ABC program offers an incentive for technology adoption but does not calculate any carbon benefits from increased productivity.

Calculated emission intensities are consistent with Figueiredo et al. (2015), which show estimates including SOC sequestration in *Brachiaria* pastures. Our estimates are significantly lower than previous studies (Cederberg, Meyer, and Flysjö 2009; Ruviaro et al. 2014; Cardoso et al. 2016; Gerber et al. 2013) this is partially because we modelled a stocking-finishing system in contrast to whole cycle systems. However, most of the differences in the emission estimates are explained by the fact the other studies do not incorporate SOC sequestration into emission intensities. Indeed, De Oliveira Silva et al. (2016) suggest that accounting for SOC in improved grazing systems could lead to a counter-intuitive result where increasing production could actually lead lower emissions than decreased stocking in some particular beef systems. Although, it is well known that SOC doesn't accumulate *ad infinitum* and in the long, term the benefits of SOC are likely to be negligible (Brandão et al., 2013; Smith, 2014).

A deterministic model has limitations in not capturing the effects of price fluctuations. Further, the focus on profit maximization is potentially contestable, and observed behaviours in relation to the demand for ABC credit to date suggests that alternative satisficing and risk minimization behaviours might warrant exploration as part of a broader sensitivity analysis of key model parameters. Indeed Brazilian farmers have a poor appreciation of the complexity of beef systems and are generally averse to new technologies (SPRP, 2014). In this respect, a robust extension service is essential for planning, on the ground, pasture restoration and beef system improvement, which would benefit from the application of appropriate mathematical optimization.

2.6. Conclusion

The analysis provides evidence of the importance of pasture management decisions for grazed beef production systems and highlights how improved pasture management could enhance both economic and environmental outcomes relative to the traditional management scenario.

Improved pasture management has a potential role to play in SOC sequestration, potentially decreasing EI in stocking and finishing systems. The results also provide evidence of the importance of public policy to promote sustainable beef production. The ABC credit can significantly influence profitability and GHG emissions. But under highly degraded conditions and the traditional practice, access to the credit may be insufficient to encourage intensification measures. The results thus provide some of the credit conditions that may be necessary to achieve Brazil's international INDCs commitments, which hitherto have not been informed by any farm scale analysis.   The results could be extended beyond Brazil to inform sustainable intensification in countries and regions with similar grazing production systems.

Chapter 3 - Developing Marginal Abatement Cost Curves for Brazilian beef production

After article: De Oliveira Silva, R., Barioni, L.G., Albertini, T.Z., Eory, V., Topp, C.F.E., Fernandes, F.A., Moran, D., 2015. Developing a nationally appropriate mitigation measure from the greenhouse gas GHG abatement potential from livestock production in the Brazilian Cerrado. Agric. Syst. 140, 48–55. doi:10.1016/j.agsy.2015.08.011. See appendix 2.

3.1 Abstract

Brazil is one of the first major developing countries to commit to a national greenhouse gas (GHG) emissions target that requires a reduction of between 36.1% and 38.9% relative to baseline emissions by 2020. The country intends to submit agricultural emissions reductions as part of this target, with livestock production identified as offering significant abatement potential. Focusing on the *Cerrado* core (central Brazilian savannah), this paper investigates the cost-effectiveness of this potential, which involves some consideration of both the private and social costs and benefits (e.g. including avoided deforestation) arising from specific mitigation measures that may form part of Brazil's definition of Nationally Appropriate Mitigation Measures (NAMAs). The analysis used an optimization model to define abatement costs. A baseline projection suggests that beef production in the region will emit 2.6 Gt CO_2e (CO2 equivalent) from 2010 to 2030, corresponding to 9% of national emissions (including energy, transport, waste, livestock and agriculture). By implementing negative-cost measures identified in a marginal abatement cost curve (MACC) by 2030, the 2.6 Gt CO_2e could be reduced by around 24%. Pasture restoration, involving avoided deforestation, offers the largest contribution to these results. As the Brazilian *Cerrado* is seen as model for transforming other global savannahs, the results offer a significant contribution by identifying alternatives for increasing productivity whilst minimizing national and global external costs.

3.2 Introduction

Global demand for livestock products is projected to grow by 70% by 2050 (Gerber et al., 2013). This is expected to generate significant additional pressure on producers and on natural resources. Sustainable management (or intensification) will require increasing yields and efficiency in existing ruminant production systems, minimizing competition of land used for food and feed, while maximizing ecosystem services, including mitigation of greenhouse gas (GHG) emissions (Gerber et al., 2013; SOUSSANA et al., 2013; Thornton and Herrero, 2010b).

Tropical regions are implicated as potentially offering major opportunities to increase beef productivity and emissions mitigation, as current productivity levels are still relatively low and emission intensities correspondingly high (Opio et al., 2013). More productive pastures can increase soil carbon stocks, providing one of the largest terrestrial carbon sinks (Follett and Reed, 2010; Neely et al., 2009), in a pool that is a more stable form than the aerial components of forests (Soussana et al., 2010). But potential carbon sequestration in soils under grasslands far from offsets the loss of above ground vegetation in the majority of tropical areas, and therefore natural vegetation should be preserved.

Brazil is the world's second largest beef producer – 9.3 $Mt.yr^{-1}$ (14.7% of the world's total), and the largest exporter in 2012-13 (FAO, 2015). Production is predominantly pasture-based in a grassland area of approximately 170 Mha (IBGE, 2015), mostly in a humid or sub-humid tropical climate. But beef production can entail significant trade-offs, that must be managed to minimize external costs. These include the controlled expansion of agricultural area, associated deforestation, cost-effective greenhouse gas mitigation, and land competition between food and biofuels.

Analysis of historical data (Martha et al., 2012) and scenario studies conducted by the World Bank (Gouvello et al., 2011) suggest that improving beef productivity has the highest potential to buffer the expansion of other agricultural activities, avoiding further deforestation. Increasing pasture productivity can also boost soil carbon sequestration, particularly when carried out in currently degraded grasslands (Braz et al., 2013; Ruviaro et al., 2014). In addition, increasing productivity through feed supplementation may significantly reduce direct methane emissions (Berndt and Tomkins, 2013; Ruviaro et al., 2014). In this context and based on its previous National Plan on Climate Change, at the Conference of the Parties 15 (COP 15), Brazil has proposed Nationally Appropriate Mitigation Actions (NAMAs) as part of its commitment to the United Nations Framework Convention on Climate Change (Brazil, 2010). Over the period 2010-2020, the NAMAs establish targets for the reduction of Amazon deforestation by 80% and by 40% in the *Cerrado* (Brazilian Savannah), through the adoption of pasture recovery (15 Mha), and from integrated crop-livestock-forestry systems (4 Mha). With these cattle-related measures, Brazil expects to reduce net emissions by between 101 and 126 Mt CO_2-e, by 2020, which account for 61% - 73% of all mitigation in agricultural practices by the NAMA route. The NAMA proposal is enacted as part of the ambitious ABC (Agricultura de Baixo Carbono - Low Carbon Agriculture) program, which offers low interest credit lines to farmers adopting mitigation technologies (Mozzer, 2011).

This chapter investigates the cost-effectiveness of key livestock mitigation measures applicable in the *Cerrado* core (Central Brazilian Savannah); a region that contains around 35% of the Brazilian herd (Anualpec, 2013). The region is considered as central in Brazil's ascendance in global production (The Economist, 2010; The New York Times, 2007) and is still regarded as the most important region for expanding beef production in Brazil (Ferraz and Felício, 2010b). It is seen as a potential model for transforming other savannahs (Morris et al., 2012).

The analytical focus is significant because there is currently little research clearly demonstrating that mitigation through livestock management can be delivered at relatively low cost (Gurgel and Paltsev, 2014; Vogt-Schilb et al., 2015). The paper offers the first bottom-up cost-effectiveness analysis using an optimization model for Brazilian beef production. The measures evaluated are pasture restoration, feedlot finishing, supplement concentrates and protein and nitrification inhibitors. The analysis uses the outputs of a multi-period linear programming model (Oliveira Silva, 2013) (See Appendix 1) to develop a bottom-up or engineering marginal abatement cost curve (MACC), to represent the relative cost-effectiveness of measures and their cumulative abatement potential above a baseline of business as usual (Moran et al., 2010). The analysis examines the direct emissions reductions attributable to measures enacted within the notional farm gate rather than wider life cycle impacts (i.e., post farm gate), and accounts for both the private and social costs and benefits (e.g. including avoided deforestation).

This chapter offers new insights for regional policy and is structured as follows. Section 3.3 outlines the modelling structure and relevant optimization assumptions underlying the cost-effectiveness analysis and describes the MACC calculation, while section 3.4 sets out results. Sections 3.5 and 3.6 offer a discussion and conclusions.

3.3 Methods

Model Overview

Abatement potential and cost-effectiveness of measures were derived using an existing multi-period linear programming model (Oliveira Silva, 2013) (See Appendix 1 for detailed mathematical description) that simulates a whole cycle (cow-calf, stocking and finishing) beef production farm, accounting for: (i) herd dynamics, (ii) financial resources, (iii) feed budgeting, (iv) land use: pasture recovery dynamics and crops, and (v) soil carbon stock dynamics.

The model optimizes the use of the farm resources (capital, cattle, land) while meeting demand projections and maximizing profit. In this context the model is used to simulate beef production treating the *Cerrado* region as a single farm. The farm activities (i-iii) are modelled using monthly time steps, while (iv & v) are modelled using annual time steps. The model represents animals in age cohorts *k*; a steer of age cohort *k=1*, is a calf aged 6 months, and 189 kg of live weight (LW). After 3 months in the system, age cohort *k* is transferred to age cohort *k+1*, now with 222 kg of LW. The final weight is 454 kg, corresponding to *k=9* (33 months), when the animal is sold and removed from the system.

The same cohorts apply to heifers, although these can also accommodate breeding rates, where a heifer generates 1 calf per 18 month cycle, comprising 9 months of pregnancy, 6 months of lactation (Millen et al., 2011), plus 3 months of non-lactation and non-pregnancy. Half of the calves born are allocated to steers and the other half are allocated to heifers, both of age cohort *k=1*. After 4 cycles, the cows are removed from the system and slaughtered, i.e., used to meet demand.

The model also simulates feedlot finishing, and thus allows the reduction of the finishing time. It can remove a proportion of steers from exclusive grazing, inserting the animals into feedlot systems; generally only males are confined in Brazil (Costa Junior et al., 2013; Millen et al., 2009). For all cattle categories, i.e., male, female, male in feedlot and breeding females, the corresponding age cohort is associated with specific parameters: weight, mortality rate, dry matter (DM) intake, selling and purchase prices, emissions factors for CH_4 from enteric fermentation and emissions factors for N_2O from excreta. The associated coefficient values are detailed in Table S1and Table S2.

The gross margin of the *Cerrado* single region farm is maximized and calculated as the difference between the income and expenses. Income derives exclusively from the sale of finished cattle, 454 kg of LW for steers and 372 kg of LW for heifers. Farm expenses are composed of investment and maintenance costs. Maintenance costs are (i) farm maintenance and (ii) animal non-feed maintenance. Costs for (i) include working animals, machinery and equipment, veterinary equipment, telephone device, fuel, taxes and fees, totalling US$ 25.00 $ha^{-1}.yr^{-1}$ (See Table S8 for details). Costs for (ii) were calculated for each age cohort and it is composed of cost of mineral salt and expenses with health (vaccines), and animal identification (Table S1).

Land use dynamics

The model simulates land use dynamics by allocating the total area across pastures or crops; the latter being used for grain and silage production to be used for the formulation of ration for feedlot and supplementation for grazing cattle. The model allocates land into pasture, soybean and corn. In the case of pasture, the model allocates land into different productivity levels. Pasture degradation and restoration rates are key model processes that have a bearing on overall system productivity and hence emissions intensity of production.

Grassland degradation

Pasture degradation can be defined as the loss of vigour and productivity of forage. To represent the degradation process, we define six levels of Dry Matter Productivity (DMP): *A*, *B*, *C*, *D*, and *F* (Table 3.1), where level *A* is the pasture of highest productivity, and level *F* is fully degraded. If no action is taken to maintain or improve productivity of a fraction of the area in a given level, it is relocated to a lower productivity level. So, after a period of time (assumed as two years herein) category *A* degrades to category *B*, *B* degrades to *C*, and so on, until pasture *F*, thus completing a 10 years full degradation (with no management interventions).

The DMP of the pastures levels were calculated exogenously using a model that estimates seasonal pasture growth according to soil, species and climate conditions (Tonato et al., 2010). Each pasture level of DMP is associated with a carbon equilibrium value that is used to estimate changes in soil organic carbon due to pasture management.

Table 3.1: Annual dry matter productivity and equilibrium C stock values in function of land use.

Land use	DM[1] ($t.ha^{-1}.yr^{-1}$)	Soil carbon stock equilibrium[2] ($t.ha^{-1}$)
Pasture A	19.6	84.3
Pasture B	17.6	82.7
Pasture C	12.6	62.3
Pasture D	8.7	45.2
Pasture E	5.8	32.4
Pasture F	3.9	26.1
Corn (Silage)	9.0	45.0
Corn (Grain)	3.8	40.0
Soybean	2.5	45.0

[1] Estimated using the model published by Tonato et al. (2010)

[2] According to Parton (1987)

Land use change and pasture restoration

To offset the degradation process the model can allow for grassland restoration through improved forage quality by direct restoration (by chemical and mechanical treatment) or indirect restoration (by rotating with crops). For example, in a given year a pasture *A* will degrade to *B*, the optimal solution might be letting half of pasture *A* to degrade, and half be maintained to level *A*. Furthermore, the model works simultaneously with a composition of pasture DMP levels; e.g., in a given year *t*, the composition can be 4% of *A*, 10 % of *B*, 85% of *C*, and 1% of soybean. Then, at year *t+1*, the composition can change by any combination among the pasture DMP levels and crops.

For each type of land use change or restoration, there is an associated cost (Table 3.1). Costs were calculated accounting for the amount of inputs and services (e.g., nitrogen, limestone, micronutrients, forage seeds, internal transport) needed to maintain or increase the DMP level in the target pasture DMP level. For details of applied inputs, see Table S3 S3-Table S7 in **Supplementary tables**.

Table 3.2 can be read as "the cost to restore one hectare of pasture "*X*" to an improved pasture "*Y*", or in some cases, "the cost to move one hectare from land use "*X*" to land use "*Y*", where "*X*" and "*Y*" are any element in the column "Pasture/Crop". The case of *X*=*Y* (table diagonal), represents the cost of maintaining a given pasture at the current DMP level (i.e., cost of avoiding degradation) or the cost of replant a crop in the same area.

Table 3.2: Costs of pasture restoration practices and crops planting.

	Costs of pasture restoration practices/land use change[1] (US$2012.ha-1)								
Land use	Pasture A	Pasture B	Pasture C	Pasture D	Pasture D	Pasture F	Corn (Silage)	Corn (Grain)	Soybean
Pasture A	112.4	0.0	0.0	0.0	0.0	0.0	1352.6	600.0	345.4
Pasture B	149.9	72.7	0.0	0.0	0.0	0.0	1502.5	749.9	495.3
Pasture C	399.3	249.4	15.0	0.0	0.0	0.0	1751.9	999.3	744.7
Pasture D	630.0	480.0	230.7	9.4	0.0	0.0	1982.6	1229.9	975.3
Pasture D	724.6	574.6	325.2	94.6	5.6	0.0	2077.2	1324.5	1069.9
Pasture F	767.0	617.1	367.7	137.1	42.5	5.6	2119.6	1367.0	1112.4
Corn (Silage)	269.8	200.9	125.1	125.1	125.1	125.1	1630.7	1060.6	971.8
Corn (Grain)	269.8	200.9	125.1	125.1	125.1	125.1	1736.4	981.9	992.6
Soybean	269.8	200.9	125.1	125.1	125.1	125.1	1736.4	981.9	1017.7

[1] See Appendix 1 for calculation details.

Land use change (including deforestation), degrading or restoring pasture will affect the soil carbon (C) stocks. These changes are calculated by estimating the annual C stock under pasture and crops for each land use. The total accumulated C under soils is given by the sum of the C stock of each pasture DMP levels, soybean and corn.

Carbon sequestration through pasture management

Depending on the DMP, the C flux may change significantly. The model works with equilibrium values of the C stock for each type of pasture and crops. The higher the pasture productivity, the higher the C equilibrium value (Table 3.1). The equilibrium values were calculated exogenously, using simulations from the CENTURY model (Parton et al., 1987) applied to *Cerrado* biophysical characteristics and using the annual DMP calculated for each pasture category.

The model accounts for the annual carbon stocks per each land use in column 1, Table 3.1. The model transfers the accumulated carbon from year *t-1* to year *t* and calculates the variation of soil C in year *t*.

Letting $C_{t,lu}$ be the soil carbon stock (tonnes) under the land use *lu*, where $lu \in \{A, B, C, D, E, F, Soybean, Corn(silage), Corn(grain)\}$. Then $C_{t,lu}$ can be expressed by:

$$C_{t,lu} = \varphi(t,lu) + \Delta C_{t,lu} \quad \text{(Eq. 3.1)}$$

And

$$\Delta C_{t,lu} = f(\varepsilon_{lu}, C_{t-1,lu}) \quad \text{(Eq. 3.2)}$$

Eq. 3.1 is composed of the carbon transference term, $\varphi(t,lu)$, and the C sequestration term, $\Delta C_{t,lu}$. The term $\varphi(t,lu)$ accounts the transference of C from other uses to land use *lu* in year *t*; e.g., if *lu* is equal pasture *B*, and one hectare of soybean is converted in year *t* into one hectare of pasture level *B*, the carbon previously stocked under soybean has to be transferred to pasture *B*. Similarly, if some hectares are converted from pasture *B* to pasture *A*, or degraded to *C*, then part of the C stock from *B* has to be proportionally transferred from *B* to these other uses. The sequestration term, $\Delta C_{t,lu}$ is written as a function of the difference between the previous C stock $C_{t-1,lu}$, and the C stock equilibrium value, ε_{lu}. Hence the further the previous stock is from the equilibrium value, the more C will be up taken. Conversely, if due to the land use change, or degradation, the C stock becomes greater than the equilibrium value, there will be negative C sequestration, i.e., a loss of C stock. These modelling approaches follow the concepts suggested by Eggleston et al. (2006) and Vuichard et al. (2007). The extended version of Eq. (3.1) and (3.2) are presented in Appendix 1.

Deforestation due to cattle ranching

For pasture area we use the projections published by Gouvello et al. (2011) combined with an endogenous deforestation term. Let LU_t be the total area at year t; a_t the exogenous projections; and D_t the endogenous term that represents further area expansion. Then for every year:

$LU_t = a_t + D_t$ (Eq. 3.3)

The deforested area will cause a loss of carbon stocks in natural vegetation and influence soil C; and directly influences the transference term in eq. (3.1), i.e., loss of soil organic matter (SOM). Both vegetation carbon stocks and SOM are accounted to represent the emissions associated with deforestation.

There is limited quantitative research accounting for the dynamics of pasture productivity following deforestation. In accordance with the best available information, the model allocates new converted areas into the system in pasture category *C* (the highest without nitrogen fertilization), as soil carbon also can increase or decrease values after deforestation (Maia et al., 2009) and pasture productivity is relatively high after conversion due to higher soil organic matter mineralization (Martha et al., 2012). In this analysis, we assumed the cost of opening new areas is zero because the cost of conversion the *Cerrado* into pastures can be offset by timber sales and land value appreciation (Bowman et al., 2012).

Another assumption is that the model cannot discard land endogenously, neither does it allow fallow in any year of the planning period. This assumption is based on the fact that cattle ranchers are not allowed to let their properties be unproductive; otherwise the land can be confiscated by the government for agrarian reform (Federal Law 8.629 - www.planalto.gov.br/ccivil_03/leis/l8629.htm).

Baseline construction

Land use change scenarios need to be mapped onto a plausible baseline for land use activity. The baseline scenario is based on national forecasts of beef demand and grassland area for Brazil, from 2006 to 2030 (Gouvello et al., 2011). The assumption is that the attributable *Cerrado* pasture area and beef demand share are a fixed proportion of the national projections. In 2006, the *Cerrado* pasture area represented 34% of the national total (IBGE, 2015). The model then assumes that *Cerrado* pasture area corresponds to 34% of Brazil's pasture area, and this proportion is constant during the studied period (2006-2030). Similarly, as there is no data for regional demand, we assumed demand to be proportional to area, i.e., demand for *Cerrado* is also equivalent to 34% of national demand, this percentage is very close to the 35% figure estimated by Anualpec (2013).

In the model, increased productivity occurs by means of investments in technologies, e.g., pasture restoration, supplementation and feedlot animals. The baseline scenario has limited adoption of these measures, implying constant productivity. We assumed that pasture restoration is allowed in the baseline only to avoid degradation, but it is constrained to maintain productivity at 2006 levels (10 $t\text{-}DM.ha^{-1}.yr^{-1}$, as calculated in Appendix 1). Combining this constraint with projected increased demand pushes the model to open new areas if it is necessary to meet the growing demand for beef.

The current adoption rate of feedlot finishing in Brazil is around 10% of the total herd. We assumed this proportion to be constant in the baseline, a rate that is in counterpoint to a higher level of penetration of this measure in a mitigation counterfactual.

GHG emissions sources

The model calculates GHG emissions using emissions factors for activities within the farm gate. GHG emissions associated with the 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 direct emissions from N fertilization; (d) CO_2 from deforestation; and (e) CO_2 from pasture degradation and land use change from pasture to crops. Items (a) and (b) depend on herd composition: each age cohort of males and females (heifer or cow) has an associated emission factor of CH_4 and N_2O calculated using Tier 2 methodology (Eggleston et al., 2006), see Table S1and Table S2. Due to the lack of studies in Brazilian conditions, for (c), we used the Tier 1 IPCC default factor of 1% (Eggleston et al., 2006). The emissions from (d) are calculated using coefficient of loss of natural vegetation per deforested area. The average carbon loss of natural vegetation due to deforestation was estimated as 34.6 tonnes of C per hectare, in accordance to Eggleston et al. (2006) and Bustamante et al. (2012). For (e), the emissions are calculated according to Eq. (3.1) and (3.2).

Mitigation Measures

The selection of GHG mitigation measures was based on literature review and expert opinion regarding the relevance and applicability of the technologies to Brazilian livestock production and conditions. The measures evaluated are: concentrate supplementation, protein supplementation, pasture restoration, nitrification inhibitors and feedlot finishing. Although the latter is already in the baseline, we investigated a higher adoption rate of this technology.

Modelling assumptions for these measures related to the effects the measures have upon the gross margin and emissions are detailed in Table 3.3.

Table 3.3: Selected livestock mitigation measures.

Mitigation measure	Description	Cost[1]	Unit	Reduces emissions by:	Adoption rate target
Feedlot finishing	When cattle weight is around 80% of the slaughter weight it is removed from pasture and grass to feedlot on a diet with ration of balanced protein and energy content	9.12	$\$.head^{-1}.mth^{-1}$	Shorter animal life cycle by increasing weight gain	15% of the total finished animals.
Nitrification inhibitors	Application of Agrotain Plus® together with urea used as fertilizer; 3 g per Kg of applied nitrogen[2]	61.44	$\$.t^{-1}$	Reduced conversion of nitrogen to the GHG nitrous oxide (nitrification)	Optimized
Pasture restoration	Improving pasture forage productivity by soil chemical and mechanical treatment.	Table 3.2	$\$.ha^{-1}$	Avoiding the need for additional pasture land and increasing organic carbon sequestration	Optimized
Supplementation concentrate	Feeding cattle via grazing and a ration with a high energy content. Grazing steers with 421 kg of LW can be selected for concentrate supplementation. The supplementation takes 2 months and the final weight is 490 kg	3.07	$\$.head^{-1}.mth^{-1}$	Shorter animal life cycle by increasing weight gain	Optimized
Supplementation protein	Feeding cattle via grazing and a ration with a high protein content. Calves (189 kg) can be selected (only in March) to be supplemented with protein. The steers are finished after 15 months, with 481 kg	1.15	$\$.head^{-1}.mth^{-1}$	Shorter animal life cycle by increasing weight gain	Optimized

[1] In the case of supplementations the values refer to non-feed costs, for feed costs see ration formulation (Table 3.4)

[2] According to manufacturer's recommendation (http://www.agrotain.com/us/home).

Concentrate and protein supplementation

Both measures involve supplementing the feed of grazing steers; e.g., feed is composed of forage and supplements. It is expected that these measures reduce emissions since animals gain weight faster and take less time to be finished.

Table 3.4: Rations (supplements) formulation and costs.

Crop	Ration Formulation (%)[1]			Cost[2]
	Feedlot	Concentrate	Protein	(US\$.kg^{-1})
Corn (grain)	83	80	15	PBF
Corn (Silage)	11	0	0	PBF
Soybean	5	17	39	PBF
Urea	0	2	12	1.19
Mineral Salt	1	1	19	0.84
NaCl	0	0	15	1.19

[1] Rations were formulated by using the software Invernada (minimum cost ration formulator) (Barioni, 2011)

[2] PBF = Produced by the farm, i.e., corn and soybean are not purchased but produced endogenously in the model.

Biological coefficients, e.g., mortality rate, weight, DM intake, and emissions factor for steers fed with supplementations can be found inTable S2.

Pasture restoration

This measure works in the model by avoiding deforestation and because restoration boosts carbon soil uptake. In contrast to the baseline scenario, to evaluate this measure, the fixed DMP baseline constraint was removed.

Nitrification Inhibitors

The measure works by avoiding a proportion of the N in fertilizer or manure being converted into N_2O, i.e. nitrification and denitrification process (Abbasi and Adams, 2000). To date there have been no studies detailing the reduction in N_2O emissions for Brazilian pastures when nitrogen inhibitors are applied. A 50% reduction of direct N_2O emissions is assumed in this paper - as found by Giltrap et al. (2011) for a New Zealand study. We assumed that this measure is applicable only over the N used for pasture and crops fertilization. The reason is that most of the Brazilian herd is based on a grazing system where it is unfeasible to apply inhibitors to animal excreta.

Feedlot finishing

Like supplementation, this measure works by reducing the cattle finishing time since feedlot animals are fed only by ration (with the formulation described in Table 3.4). Only steers can be selected to model in the feedlot system. The adoption rate was arbitrarily assumed to be 15% of the total finished herd, since in the baseline the adoption rate is 10% of the total finished herd, the measure can be stated as: increasing by 50% over the baseline adoption rate.

Marginal abatement cost curve

A MACC can be used to represent the relative cost-effectiveness of different abatement options and the total amount of GHG that can be abated by applying mitigation measures over and above a baseline scenario. The aim is to identify the most economically efficient manner to achieve emissions reduction targets, where the cheapest units of greenhouse gas should be abated first (Moran et al., 2010).

MACC analysis can be derived by means of a top-down analysis – which usually makes use of a general equilibrium model and emissions are calculated endogenously, or by a bottom-up or engineering analysis (MacLeod et al., 2010). This paper takes a bottom-up approach, where the individual abatement potential of measures and their costs are individually modelled.

The MACC can be presented in form of a histogram, where the C abatement potential lies on the x-axis, and the cost per tonnes of abatement in the y-axis. The abatement potential of a measure *m* (AP_m) is calculated as the annual average of the difference between the business-as-usual (baseline) total GHG emissions (E_{BAU}) and the total emissions under the mitigation measure scenario (E_m) during the production period *T*:

$$AP_m = \frac{E_{BAU} - E_m}{T} \quad \text{(Eq. 3.4)}$$

The cost-effectiveness of measure *m* (CE_m), therefore, is calculated by:

$$CE_m = \frac{GM_{BAU} - GM_m}{AP_m} \quad \text{(Eq. 3.5)}$$

Where GM_{BAU} and GM_m are, respectively, the gross margin in the baseline scenario and the gross margin in the scenario with the measure *m* implemented.

As observed in Eq.3.4 and Eq.3.5, AP_m and CE_m are average values across the planning period.

3.4 Results

Baseline Emissions

In the baseline scenario, beef production in the *Cerrado* accounts for an average of 121.5 Mt $CO_2e.yr^{-1}$, from 2010 to 2030. This value includes enteric fermentation, animal waste (emissions from excreta), soil fertilization emissions, pasture (due to the loss in C stocks), and deforestation driven by cattle production (Fig. 3.1). The accumulated emissions from 2010 to 2020 account for about 1,249 Mt CO_2e or 2,551 Mt CO_2e from 2010 to 2030.

In relative terms, enteric fermentation makes the biggest contribution to the total: 66% of emissions, followed by deforestation, with 26%. The results also show that pasture degradation is a considerable source of emissions, accounting for an average of 8.35 Mt $CO_2e.yr^{-1}$ (an average of 0.06 t $CO_2e.ha^{-1}.yr^{-1}$), the equivalent to 4% of emissions or the same proportion as animal waste (Fig. 3.2).

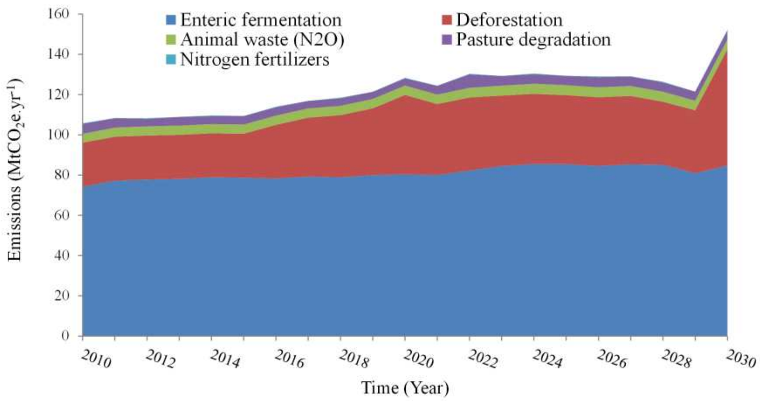


Figure 3.1: Baseline emissions of beef production in the Brazilian Cerrado for the 2010-2030 period.

Gouvello et al. (2011) suggests that total national GHG emissions from energy, transport, waste, livestock and agriculture, will be around 1.70 Gt CO_2e by 2030. The results presented here suggest that beef production in the *Cerrado* will be responsible for about 152 Mt CO_2e in 2030, corresponding to 9% of total national GHG emissions.

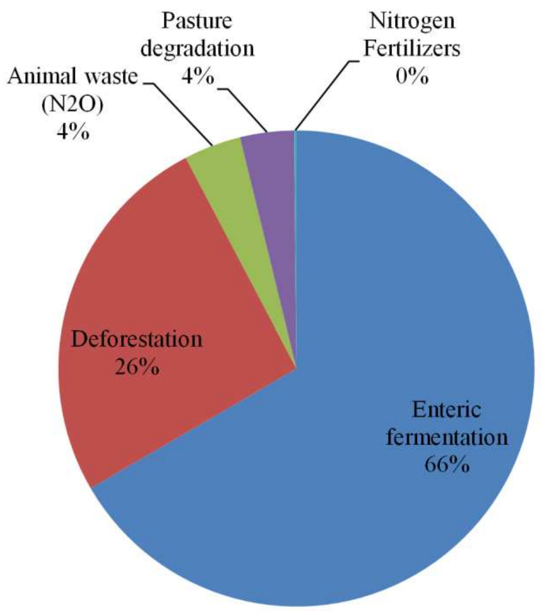


Figure 3.2: Share of the main GHG emissions sources from beef production in the Brazilian Cerrado.

Figure 3.2 relates to the proportion of each source in relation to the accumulated emissions for the period 2010-2030.

In the baseline scenario, without increasing productivity, an average deforestation rate of 246.1 10^3 $ha.yr^{-1}$ would be required to meet the beef demand projections.

Emissions attributed to the use of fertilizers were not significant, accounting for an average of 0.2 Mt $CO_2e.yr^{-1}$. This was expected, since small amounts of N are used to fertilize *Cerrado* pasture soils (Cederberg et al., 2009).

Cost-effectiveness analysis

For policy purposes it is important to detail the relative cost of emissions mitigation measures. Three of the five mitigation measures simulated, - concentrate supplementation, protein supplementation, and pasture restoration - have negative cost-effectiveness: US$-8.01. t CO_2e^{-1}, US$-2.88. t CO_2e^{-1} and US$-0.05. t CO_2e^{-1}, respectively (Fig. 3.3). Adopting these measures implies cost savings while reducing emissions. These measures work by balancing the loss of DM production during the dry months. The *Cerrado* biome is predominantly seasonal tropical, meaning dry winters and rainy summers, with lower pasture productivity during the dry months. If cattle are supplemented with concentrates or protein they can be finished earlier, thereby reducing emissions.

Due to the large applicable area (approximately 60 Mha), and given the current low productivity of 10 t $DM.ha^{-1}.yr^{-1}$, pasture restoration provides the biggest opportunity for reducing emissions in the region.

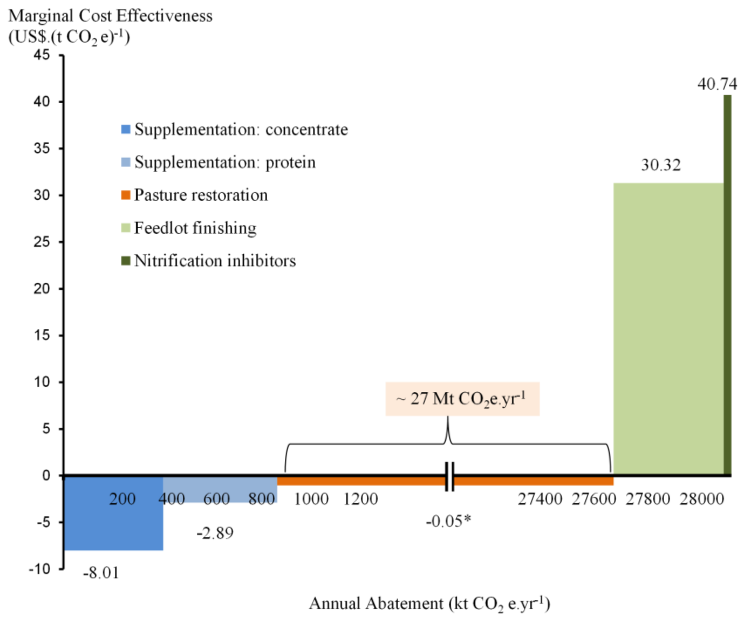


Figure 3.3: Marginal abatement cost schedule of key mitigation measures applicable to beef production in the Cerrado.

* Not in scale. The abatement potential (x-axis) and cost effectiveness (y-axis) of each measure was calculated as the average values obtained by adopting the measure over the 2006-2030 period.

The abatement potential (AP) for pasture restoration is 26.9 Mt $CO_2e.yr^{-1}$, comprising of two components: C sequestration and avoided deforestation, the latter accounting for 96% of this AP. Despite improved pasture productivity, less area is used to meet the same demand relative to the baseline, what means forage availability optimally matches that required for demand. In a scenario of increased forage productivity and higher beef demand, methane emissions would rise as result of increased animal numbers. Pasture restoration would improve the *Cerrado* average productivity from 10 to 11.2 t $DM.ha^{-1}.yr^{-1}$, an increase of 12% relative to the baseline. This increase would lead to an average C sequestration rate of 0.32 t $CO_2e.ha^{-1}.yr^{-1}$. This is a low C uptake potential when compared to values found by Maia et al. (2009), which showed that C sequestration rates of 2.24 t $CO_2e.ha^{-1}.yr^{-1}$ can be achieved in well-managed pastures in *Cerrado*. The carbon sequestration rate however, reflect the 2006-2030 period, after which, and in the long term, as pastures are intensified it will eventually reach equilibrium and therefore no more carbon is likely to be sequestered.

The AP of feedlot finishing is 470 kt $CO_2e.yr^{-1}$, but the measure cost-effectiveness US$ 13.32 t CO_2e^{-1} is high relative to supplementation.

Nitrification inhibitors are the least cost-effective measure considered. But this analysis only considered the application to N used for pasture and crops fertilization and excluded the application to animal excreta.

The results indicate that restoring degraded lands is the biggest opportunity for reducing emissions in the *Cerrado*. The AP of this measure is about 20 times greater than all the other measures combined.

An important assumption underpinning the MACC relates to the assumed measure adoption rates. With exception of feedlot finishing, the adoption rates are optimized, meaning the rates that maximizes the gross margin in the model.

Figure 3.4: Mitigation measures adoption rate.

Mitigation Measure	Adoption rate	Unit
Supplementation: concentrate	12	%[1]
Supplementation: protein	2.2	%
Pasture restoration	314.7	10^3 $ha.yr^{-1}$
Feedlot finishing	15	%
Nitrification inhibitors	12.78	$g.ha^{-1}.yr^{-1}$

[1] Adoption rates for feedlot, protein and concentrate supplementation are calculated as the percentage of the total finished animals. The adoption rate of pasture restoration is the annual average area of restored pasture.

3.5 Discussion

To meet increasing domestic and export demand, the government of Brazil recognizes the need to foster sustainable agricultural intensification, which implies increased resource productivity while minimizing significant domestic and global external costs implicit in GHG emissions and deforestation. The results presented here suggest that a significant contribution to this objective can be made by targeting specific measures to improve yield. Specifically, pasture restoration, supplements and feedlot measures could reduce sector emissions by 24.1% by 2030. Moreover, by adopting only negative-cost measures, it is possible to abate about 23.7% of baseline livestock emissions in the *Cerrado*, up to 2030. According to our results the restoration of degraded pastures offers the greatest abatement potential, involving the restoration of an average of 314.7 10^3 $ha.yr^{-1}$ in *Cerrado* grasslands.

Currently, it has been estimated that 50 % to 80 % of pastures in the Amazon and *Cerrado* are degraded (Macedo et al., 2014; Peron and Evangelista, 2004). Achieving a higher rate is likely to entail some initial investment costs to promote modified production practices and this is the purpose of the government's ABC program. ABC is an ambitious plan created to stimulate farmers and ranchers to adopt mitigation measures including restoration of degraded pastures, helping the country to meet the reduction targets presented at COP 15. ABC is the biggest sustainable agriculture fund running in Brazil, with a key objective of disbursing subsidized credit to the agricultural sector. The plan currently targets the recovery of 15 Mha in 10 years, which will lead to reductions up to 104 Mt CO_2e, roughly 64% of the program total mitigation potential. But it does not include other relevant measures such as feed supplementation measures, which would normally be considered as privately profitable anyway.

The outcome of the ABC plan remains to be evaluated, but initial indications suggest that uptake of credit has been slower than anticipated (Claudio, 2012). Recent evidence from the Amazon Environmental Research Institute suggests that several institutional barriers have retarded the program, including a lack of publicity and information about the aims and the benefits of the program, difficulties in complying with program requirements, a lack of technical assistance, and producer scepticism about the private economic benefits of measures that are predominantly designed to address global external costs (Stabile et al., 2012).

Producers also perceive transaction costs in program compliance and a lack of basic infrastructure (Rada, 2013) that is needed to support increased productivity. In short, the ABC plan is confronting similar behavioural barriers in relation to non-adoption, identified in other mitigation studies, e.g. Moran et al. (2013), which need to be addressed before wider measure adoption can be expected.

3.6 Conclusion

This paper highlights how resource efficiency measures can be enacted (notionally within farm gate) in the *Cerrado* biome to help reconcile competing objectives of private yield improvements and the reduction of external costs. The analysis responds to the need to demonstrate the possibilities for sustainable intensification, allowing Brazil to meet economic growth ambitions for the sector.

The key finding from the use of the economic optimization model is the representation of the cost-effectiveness of key mitigation measures. Specifically, that pasture restoration is the most promising mitigation measure in terms of abatement potential volume and that it offers a cost saving for the livestock sector. By adopting these measures - pasture restoration, concentrate and protein supplementations - the *Cerrado* could reduce 23.7% of its emissions by 2030, while the total abatement potential of adopting all measures is 24.1%.

The analysis presented here has a number of caveats that potentially warrant further research. These include a more detailed representation of the biophysical heterogeneity of the *Cerrado* biome, more detailed treatment of the deforestation (and hence land sparing) processes and relaxation of the assumed equilibrium supply and demand conditions in the optimization model.

Nevertheless by highlighting cost-effective policy options, this paper contributes to our understanding of sustainable intensification processes as relevant to Brazilian livestock production.

Chapter 4 - Designing the livestock contribution to the Brazilian Intended Nationally Determined Contribution (INDC)

4.1 Abstract

Brazil is the first developing country to provide an absolute emissions cut as its Intended Nationally Determined Contribution (INDC), which seeks to reduce greenhouse gas (GHG) emissions by 37% below 2005 levels by 2025 and 43% by 2030. The INDC is also noteworthy in focussing on emissions from deforestation control and land use change. Agricultural intensification is a key component of the new commitment, 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 can be delivered by this measure, and to show a result that underpins the INDC target of zero deforestation in all Brazilian biomes. The analysis provided the basis of the INDC offered by the Government of Brazil 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.

4.2 Introduction

Brazil's INDC, 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 covers the decade 2020-30 and 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, 2010). 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 Brazilian Amazon and by 40% in the *Cerrado* (Brazilian savannah – Figure 4.1), achievable through the adoption of pasture recovery, and integrated crop–livestock–forestry systems (Mozzer, 2011). These measures aim to reduce emissions directly by increasing soil organic carbon (SOC) stocks, and indirectly through land sparing, hence avoided deforestation.

The INDC poses a challenge to reconcile emissions reduction, deforestation and biodiversity, with ambitious goals for livestock production, predicted to grow by 18% over the decade 2014-24 (OECD, 2016). In essence, the country is betting on large-scale sustainable agricultural intensification (SAI) (R de Oliveira Silva et al., 2016; Garnett et al., 2013; Rockström 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 parameterised for the main biomes: *Cerrado*, Amazon and Atlantic Forest, accounting for around 37%, 28.5% and 23.5% of national beef production respectively (IBGE, 2015). The analysis was the basis of the INDC contribution and this paper outlines some of the outstanding challenges to the likelihood of meeting the target when including agriculture and land use sectors in the commitment.

Figure 4.1: Brazilian main beef cattle production systems (biomes).

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). There has always been a tension between these objectives and national economic growth, and an extensive literature on the causes of deforestation has highlighted the role of extensive pasture expansion , and the consequent loss of valuable ecosystem services (Nepstad et al., 2014a). However, recent success in arresting deforestation (Lapola et al., 2014; Macedo et al., 2012; Nepstad et al., 2014a) and associated emissions has arguably received less attention.

Promotion of beef production has underpinned Brazil's economic ascendance into global commodity markets, accounting for 15.5% of global production by 2013 (FAO, 2015). Beef exports have long been competitive, mainly because predominantly grazed pastures 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 step-change accelerating Brazil's global market ascendance (Rada, 2013; The Economist, 2010). 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. Moreover, despite this step-change, average stocking rates nationwide remain low, i.e., around 1 head per hectare ($hd.ha^{-1}$) compared to a potential carrying capacity exceeding 2 $hd.ha^{-1}$ (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 (Barona et al., 2010; Nepstad et al., 2014b). Peaking in 2004, annual deforestation rates have since decreased significantly and are currently around 80% lower than the 1995-2005 average. Census 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 (IBGE, 2015). Deforestation in all Brazilian biomes has fallen to its lowest rate since satellite monitoring began (Lapola et al., 2014). Correspondingly, national emissions inventory data (MCTI, 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 (Arima et al., 2014; Lapola et al., 2014; Macedo et al., 2012; Soares-Filho et al., 2010). 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 (MCTI, 2014).

This apparent decoupling of agricultural output and deforestation, and scope for further pasture restoration, provides the basis for an INDC that is potentially consistent with accommodating an upward trend in livestock production to meet increasing demand. In essence Brazil's INDC 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. Since around 90% of Brazilian cattle are pasture-fed (Anualpec, 2013), intensification is mainly through restoration of degraded pastures. The livestock sector contribution to the INDC is thus defined in terms of the area of degraded pastureland required to be cost-effectively restored over 2020-30, while meeting livestock product demand and deforestation targets in all biomes

4.3 Methods

Two models were employed to calculate restoration area: the Demand Constrained Restored Area model (DCRA) is a single equation model based on a predicted increase in demand, increasing animal efficiency, and total pasture area variation. The second model EAGGLE (de Oliveira Silva et al., 2015a; R de Oliveira Silva et al., 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. EAGGLE defines a set of direct restoration practices for pasture formation, each consisting of a different level of application; i.e. inputs to the soil and machine operations. The restoration area is defined as the sum of the adoption rate of the individual restoration practices over the decade 2020-30.

The analysis is based on data for observed beef production and pasture area (FAO, 2015; IBGE, 2015) for the period 1995 -2010, and projected baseline demand D_{BAU} for 2011-2030 (Gouvello et al., 2011). Alternative lower (D_{Low}) and higher (D_{High}) demand scenarios were also explored, corresponding to 20% lower and higher demand relative to D_{BAU} by 2030.

Projected pasture area (2011-2030) under a policy-on scenario (A_{INDC}) assumes full accomplishment of the NAMA and INDC targets, i.e., reduction of Amazon deforestation by 80%, and by 40% in the *Cerrado* by 2020, and zero deforestation in all biomes by 2030. A_{BAU} is a baseline or counterfactual scenario to the achievement of the A_{INDC} scenario. A_{INDC} is a land sparing scenario requiring more intensification than A_{BAU} for the same demand. To produce the same beef output in A_{INDC} as in A_{BAU}, EAGGLE intensifies production by improving pasturelands through restoration and increasing animal efficiency by finding the optimal rate of adoption of feedlot finishing, semi-confinement and feed supplementation. These alternatives can accelerate production while reducing cattle direct emissions (CH_4 and N_2O) by shortening life cycles, but only at an increased investment cost.

The analysis used two models to estimate the restoration area requirement. The Demand Constrained Restoration Area (DCRA) model, a simplified single equation model to calculate the total restored area based on predicted increase in demand, increasing animal efficiency, and total pasture area variation, and the EAGGLE model (R de Oliveira Silva et al., 2016), a detailed linear program focused on the optimization of pasture degradation and restoration processes. EAGGLE was also employed for cost-effectives analysis; estimates of average direct costs per hectare (costs of technologies) and mitigation potential in terms of avoided deforestation and soil organic carbon sequestration through improved grasslands.

DCRA model

The DCRA model 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 an increase in animal productivity (i.e., carcass yield). The DCRA model is given by

$$\Rightarrow \frac{dR}{dt} = \frac{\frac{1}{C(t)}\left(\frac{\partial P}{\partial t} - N(t)\frac{dC}{dt}\right) - s_D \frac{dA}{dt}}{\left(s_R - s_D\right)} \qquad (4.9)$$

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.

Pasture restoration is a major part of the Brazilian NAMA (Mozzer, 2011) and INDC (Brazil, 2015) and is operationally encouraged through a government-funded bank credit line for low carbon agriculture. Beef production is the major grassland based activity in Brazil. Therefore, pasture restoration area targets should harmonize with projected demand for beef in order to avoid under and over production and negative impact on prices. Pasture restoration area has been also been estimated by large mathematical programming models (EAGGLE model) but the development of a single equation model is useful to improve understanding and transparency of the estimates and the interpretation of such large models' results. The equation is derived to determine pasture restoration area based on beef demand and to use it to analyse the responses of pasture restoration to their conditioning factors in the Brazilian context

The DCRA mathematical derivation

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

$$\mathrm{N(t)=s_D D(t)+s_R R(t)} \quad (4.1)$$

Where s_D and s_R are respectively the stocking rates (heads 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:

$$\mathrm{A(t)} = \mathrm{D(t)} + \mathrm{R(t)} \quad (4.2)$$

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

Replacing (4.2) in (4.1):

$$\mathrm{N(t)} = \mathrm{s_D A(t)} + \mathrm{R(t)}\left(\mathrm{s_R} - s_D\right) \quad (4.3)$$

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

$$\frac{\partial N}{\partial t} = s_D \frac{dA}{dt} + \left(s_R - s_D\right)\frac{dR}{dt} \quad (4.4)$$

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 (4.4):

$$\Rightarrow \frac{dR}{dt} = \frac{\frac{\partial N}{\partial t} - s_D \frac{dA}{dt}}{\left(s_R - s_D\right)} \quad (4.5)$$

In addition to (1), *N(t)* can also be written as a function of beef demand and animal productivity:

$$\mathrm{P(t)} = \mathrm{C(t)N(t)} \quad (4.6)$$

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*:

$$\frac{\partial P}{\partial t} = N(t)\frac{dC}{dt} + C(t)\frac{dN}{dt} \quad (4.7)$$

Rearranging (4.7)

$$\frac{dN}{dt} = \frac{1}{C(t)}\left(\frac{\partial P}{\partial t} - N(t)\frac{dC}{dt}\right) \quad (4.8)$$

Replacing (4.8) in (4.5):

$$\Rightarrow \frac{dR}{dt} = \frac{\frac{1}{C(t)}\left(\frac{\partial P}{\partial t} - N(t)\frac{dC}{dt}\right) - s_D \frac{dA}{dt}}{(s_R - s_D)} \quad (4.9)$$

dC/dt can be written as:

$$\frac{\mathrm{dC(t)}}{\mathrm{dt}} = kC(t) \quad (4.10)$$

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

Eq. (4.9) 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)*), stoking 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 used values for the parameters and variables above-mentioned are presented in the Table 4.1.

Table 4.1: Assumed values for the variables and parameters

Variable/parameter	Values	Unit[1]	Reference
dP/dt	1.73	Mt CWE.y^{-1}	(Gouvello et al., 2011)
N(t)	215.90	Mhd	(Gouvello et al., 2011)
P(t)	11.40	Mt CWE	(Gouvello et al., 2011)
dA/dt	-10.00	Mha.y^{-1}	This work
s_D	0.50	hd.ha^{-1}	(IBGE, 2015)*
s_R	2.00	hd.ha^{-1}	(IBGE, 2015)*
k	0.070	t.hd^{-1}.y^{-1}	(CNPC, 2016)

[1] y = 10 years

* Based on IBGE (2015) stoking rates frequency.

The EAGGLE model

The Economic Analysis of Greenhouse Gases for Livestock Emissions (EAGGLE) model simulates a whole cycle (cow-calf, stocking and finishing) beef production farm accounting for herd dynamics, financial resources, feed budgeting, pasture recovery dynamics and crops plantation for feedlot and grazing cattle supplementing, and soil organic carbon dynamics. The model optimizes the use of farm resources (capital, cattle, land) while meeting annual demand projections and maximizing profit (gross margin). In this analysis EAGGLE treats the biomes Amazon, *Cerrado* and Atlantic Forest as independent systems, i.e., no cattle transfer is assume among the biomes and beef production is simulated independently in the biomes, each treated as a single farm. The model simulates feedlot finishing, and allows 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).

Pasture restoration

EAGGLE defines a set of direct restoration practices (*P1*, *P2*, *P3*, *P4* and *P5*) for pasture formation, each consisting of a different level of applied technology; i.e. inputs into the soil and machine operations, Table 2.7 The total recovered area in a given year *t* (R_t) derived by summing the individual areas that were subjected to the applied technologies in that year, i.e., $R_t = P1_t+P2_t+P3_t+P4_t+P5_t$, where A_t represent the area converted (or restored) from any less productive pasture to pasture *A* in year *t*.

EAGGLE 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 pasture degradation and restoration dynamics is presented as supplementary information in De Oliveira Silva et al. (2016). Table 4.2 synthetises the restoration practices applicable to Brazilian grasslands. The model optimizes (profit maximization) pasture management based on decisions on whether restore, maintain or degrade a pasture level defined in Table 4.2.

Table 4.2: Description of pasture type formation (level of technology) and productivity (dry matter per area) for the Brazilian Cerrado.

Pasture	Pasture formation (ilustrative description)[1]	Cost (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
P2	Mowing + dolomitic limestone + single phosphate + brachiaria seeds + micronutrients + 45kg of N	617.1	17.6	82.7
P3	Mowing + dolomitic limestone + single phosphate + brachiaria seeds	367.7	12.6	62.3
P4	Mowing +dolomitic limestone + single phosphate	137.1	8.7	45.2
P5	Mowing	42.5	5.8	32.4
P6	No intervention[4]	0	3.9	26.1

[1] The full description of inputs and machinery operations are presented as supplementary information in De Oliveira Silva et al. (2016)

[2] Annual dry matter accumulation rates are presented for simplification, 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 DMP calculated for each pasture category.

[4] *P6* represents pasture at minimum productivity level (ecosystem equilibrium).

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 (R de

Oliveira Silva et al., 2016). The 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, 2010).

Pasture and demand projections

Pasture area time series (PATS) were developed for the Brazilian Amazon, *Cerrado* and Atlantic Forest encompassing historical (1996-2010) and projected estimates (2011-2030). The Agricultural Census of 1996 (IBGE, 2015) provided the initial pasture area estimates while sources of observed data were used to estimate pasture area variation (LUC_p). Historical sources of data (Brazil, 2010) included: Agricultural Census (1996 and 2006); land use change reports from GHG emissions inventories (1994 and 2002); satellite data, and indirect estimates of pasture area variation ($LUC_{p,i}$).

$$LUC_{p,i} = LUC_n - LUC_c - LUC_o \quad (4.11)$$

Where LUC_c are annual cropping area variation based on Census data and the Municipal Agricultural Production survey (IBGE, 2012) and LUC_n are annual rates of natural vegetation conversion to agriculture (IBAMA, 2016), and LUC_o is the annual variation of other land (IBGE, 2015).

For the PATS baseline, projections of LUC_n and LUC_c were based Gouvello et al. (2011) baseline scenario. The NAMA and INDC scenario estimated $LUC_{p,i}$ through Eq. 4.11 assuming LUC_n targets for 2020 and 2030 are met all other as the baseline. PATS for Atlantic Rainforest were the same in all scenarios because there was no NAMA and INDC target for that biome.

Historical beef production was derived from national-level National Council of Beef Production estimates (CNPC, 2016). National level projections (Gouvello et al., 2011) of beef production were calibrated for continuity with the historical series The national production was allocated to each of the biomes assuming beef productivity as proportional to the stocking rates of the IBGE 2006 Census data (IBGE, 2015).

The varied demand projections were generated through interpolation of the baseline projection (D_{BAU}) so that the lower demand (D_{Low}) and the higher demand (D_{High}) were respectively 20% lower and 20% higher that D_{BAU} by 2030.

Bioeconomic data

Costs related to the restoration practices specific to the *Cerrado* are presented in, full details of applied inputs (soil chemical treatment) and farm operations (soil mechanical treatment) can be found in De Oliveira Silva et al. (2016, 2015a). 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* values, cattle prices in the Amazon and Atlantic Forest were respectively 4% higher and 4% lower than for the *Cerrado* (Conab, 2016)

Pastures productivity for the pasture formations *P1* to *P6* (Table 3.1) in the biomes were estimated using the methodology detailed in De Oliveira Silva et al. (2016), using the Invernada software (Barioni, 2011) which works with monthly average historical climate data and amount of N applied to estimate potential accumulation rates for the main grass species in Brazil.

4.4 Results

The DCRA model suggests over the period 2020-30, 15.10 Mha of restoration is necessary to meet demand and the zero deforestation target by 2030. EAGGLE estimates the nationwide restoration potential 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.

Table 4.3 shows projected beef demand to be met by 2020 and 2030, and EAGGLE estimates of herd size, restoration area and necessary total investment costs of restoration varying by demand scenario and biome.

Table 4.3: Beef demand and model results: herd estimates, restoration area and costs by biome.

	Demand	Cerrado	Amazon	Atlantic Forest	Other biomes	Brazil
Demand by 2020 (Mt CWE)	D_{Low}	4.10	2.76	2.26	1.13	10.25
	D_{BAU}	4.60	3.10	2.60	1.13	11.43
	D_{High}	5.18	3.49	2.86	1.13	12.66
Demand by 2030 (Mt CWE)	D_{Low}	4.62	2.78	2.25	1.13	10.78
	D_{BAU}	5.72	3.44	2.86	1.13	13.15
	D_{High}	6.92	4.17	3.38	1.13	15.60
herd, avg 2020-2030 (Mhd)	D_{Low}	77.70	56.21	39.41	17.40	190.72
	D_{BAU}	91.69	65.90	46.92	17.40	221.92
	D_{High}	103.99	74.32	52.21	17.40	247.92
Recovered area (Mha)	D_{Low}	5.18	3.44	3.78		12.39
	D_{BAU}	8.91	5.23	4.28		18.42
	D_{High}	13.10	8.08	7.76		28.95
Total cost (M US\$2012.yr^{-1})	D_{Low}	146.94	104.65	106.41		358
	D_{BAU}	249.74	163.13	139.64		552.5
	D_{High}	369.74	239.29	215.75		824.77

Brazil is forecast to produce 11.43 mega tonnes of carcass weight equivalent (Mt CWE) and 13.15 Mt CWE by 2020 and 2030 respectively, with an increasing share in the *Cerrado* (43% by 2030). EAGGLE estimates show that the extent of pasture restoration nationwide is sensitive to demand scenarios. Higher demand requires more intensification as land expansion is constrained. Restoration area ranges and from 12.39 Mha to 28.9 M ha, respectively for the lowest and highest demand scenarios.

Estimated average restoration costs (i.e., total costs divided by recovered area in Table 4.3) are US\$ 28.0 ha.$^{-1}$yr^{-1}, US\$ 31.2 ha.$^{-1}$yr^{-1} and US\$ 32.6 ha.$^{-1}$yr^{-1}, respectively for the *Cerrado*, Amazon and Atlantic Forest. Table 4.3 suggests around US\$ 0.5 billion is required to meet the 18.4 Mha restoration area from 2020-30, given baseline demand, or around US\$0.8 billion if demand is 20% higher by 2030.

Figure 4.2 shows pasture area and biome emissions profiles with and without the accomplishment of zero deforestation, i.e., successful implementation of NAMA and INDC commitments, respectively indicated by the vertical timelines. The figure combines observed data 1996-2010 (dots) and model projections A_{BAU} (dashed lines) and A_{INDC} (straight lines).

Figure 4.2a shows observed pasture expansion and beef production data from 1996 to 2010 (FAO, 2015; IBGE, 2015). Figure 4.2b to 2e show emissions profiles based on Figure 4.2a pasture trajectories. Amazon emissions up to 2005 (Figure 4.2b) were largely dominated by land use change, i.e., deforestation, subsequently decreasing substantially. 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 emissions (1996-2010) were also largely dominated by deforestation (Figure 4.2c), with the exception of 2002- 2005 and 2010, when emissions from enteric fermentation were higher. 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 the baseline and NAMA and INDC scenarios respectively.

Cattle-related emissions in the Atlantic Forest biome are roughly half those from the *Cerrado* for the whole period (Figure 4.2d). Estimated emissions were dominated by pasture expansion in 1998, 2001 and 2010. Averaging 84.3 Mt $CO_2e.yr^{-1}$, emissions from the Atlantic Forest are projected to fall to 33.4 Mt $CO_2e.yr^{-1}$ from 2011 to 2030. For this biome there is no difference between baseline and the NAMA and INDC scenarios.

Figure 4.2e shows the full mitigation potential from the livestock sector. Under baseline deforestation rates, emissions (2011 – 2030) would average 1130 Mt $CO_2e.\ yr^{-1}$, while NAMA and INDC 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) (Figure 4.2e), with 97% arising from reduced deforestation in the Amazon and the *Cerrado*.

Zero deforestation by 2030 implies that the livestock sector would emit 157 Mt CO_2e compared to 1350 Mt CO_2e emitted in the same year were Amazon and *Cerrado* deforestation rates to follow baseline trends

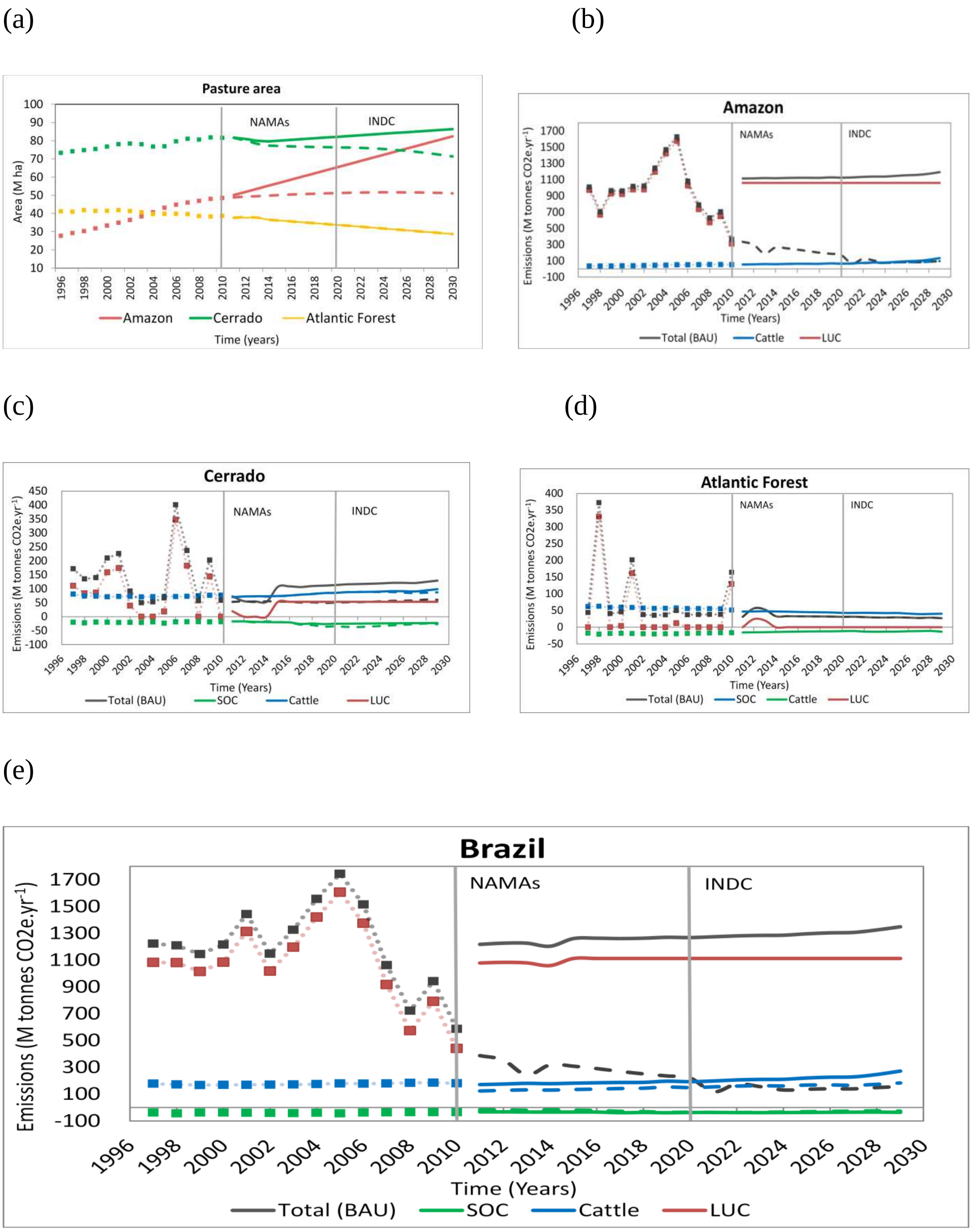


Figure 4.2: Estimates and projections of pasture area and GHG emissions pre and post NAMA and INDC implementation. Pasture area estimates using observed data 1996-2010 (dots) and projections 2011-2030 (lines) for the Amazon, the Cerrado and the Atlantic Forest under baseline and NAMA and INDC scenarios (a); GHG emission estimates (observed data) from 1996-2010 (dots) and projections (lines) under baseline, NAMA and INDC scenarios for the Amazon (b), the Cerrado (c), the Atlantic Forest (d) and Brazil (e).

4.5 Discussion

The 15.1 - 18.4 Mha estimates guided the proposal advanced by Brazil at COP21 (2015), with pasture restoration a key measure reconciling competing challenges. Empirical evidence (Arima et al., 2011; FAO, 2015; IBGE, 2015; Lapola et al., 2014; Macedo et al., 2012) supports the feasibility of the INDC, with the corollary of continued policies controlling deforestation (Arima et al., 2011), plus the provision and adoption of funding for restoration and other intensification technologies. The latter is currently provided by the ABC (*Agricultura de Baixo Carbono* - Low Carbon Agriculture) programme offering low interest credit to farmers adopting mitigation technologies including pasture restoration (de Oliveira Silva et al., 2015b; Mozzer, 2011). Our results suggest that the ABC budget of US$1.7 billion in 2012 (Brazil, 2013) exceeds the average cost of US$0.55 billion to meet estimated restoration costs. However, adoption may be more problematic, with evidence suggesting limited uptake due to the inherent risk-aversion among producers with respect to the liabilities and bureaucracy attached to ABC credit. This includes tenure requirements alternative land use implications, and declaration of their emissions.

4.6 Conclusion

Brazil's INDC is a bold statement of its scientific and intuitional commitments to reconciling its domestic and international sustainability goals. It highlights the potential role of SAI in meeting these goals and that of complementary policies that can hopefully be improved and insulated from recent political and economic change.

Chapter 5 - Changes in greenhouse gases emissions as a function of changes in Brazilian beef demand

After article: De Oliveira Silva, R., Barioni, L.G., Hall, J.A.J., Folegatti Matsuura, M., Zanett Albertini, T., Fernandes, F.A., Moran, D., 2016. Increasing beef production could lower greenhouse gas emissions in Brazil if decoupled from deforestation. Nat. Clim. Chang. 6, 3–8. doi:10.1038/nclimate2916. See appendix 3.

5.1 Abstract

Recent debate about agricultural greenhouse gases (GHG) emissions mitigation highlights trade-offs inherent in the way we produce and consume food, with increasing scrutiny on emissions-intensive livestock products (Bajželj et al., 2014; Garnett et al., 2013; Tilman et al., 2011). While most research has focussed on mitigation through improved productivity (McDermott et al., 2010; Henning Steinfeld et al., 2006), systemic interactions resulting from reduced beef production at regional level are still unexplored. A detailed optimization model of beef production encompassing pasture degradation and recovery processes, animal and deforestation emissions, soil organic carbon (SOC) dynamics and upstream lifecycle inventory was developed and parameterized for the Brazilian *Cerrado*. Economic return was maximized considering two alternative scenarios: Decoupled Livestock Deforestation (DLD), assuming baseline deforestation rates controlled by effective policy; and Coupled Livestock Deforestation (CLD), where shifting beef demand alters deforestation rates. In DLD, reduced consumption actually leads to less productive beef systems, associated with higher emissions intensities and total emissions, while increased production leads to more efficient systems with boosted SOC stocks, reducing both per kg and total emissions. Under CLD, increased production leads to 60% higher emissions than in DLD. The results indicate the extent to which deforestation control contributes to sustainable intensification in *Cerrado* beef systems, and how alternative life-cycle analytical approaches[6] result in significantly different emission estimates.

5.2 Introduction

Rising global population combined with shifting dietary preferences in emerging economies are leading to a significant increase in demand for livestock products, which is expected to double by 2050 (Tilman et al., 2011). This shift is happening in the context of global climate change and associated resource scarcities, leading to calls for sustainable agricultural intensification (SAI)(Garnett et al., 2013; Herrero et al., 2009; Henning Steinfeld et al., 2006). Although a contested concept, the SI debate highlights elements of resource use efficiency in production, combined with the management of demand or consumption (Garnett et al., 2013; Godfray et al., 2010; Smith, 2013). While persuasive, the SAI literature is limited in its illustration of the environmental and economic trade-offs that can emerge when implementing SAI measures in globally significant production systems.

Ruminant livestock is specifically implicated as a major cause of agricultural externalities in terms of GHG emissions (CH_4 and N_2O) and appropriation of land that otherwise provisions valuable ecosystem services (H Steinfeld et al., 2006). A counter-argument suggests grass-fed beef systems have significantly lower emissions when accounting for atmospheric carbon dioxide (CO_2) uptake by deep-root grasses promoting greater soil carbon (C) storage. Such systems could play a significant role in stabilising GHGs (Soussana et al., 2010). Moreover this sequestration in specific systems may off-set direct livestock emissions (Soussana et al., 2010).

Brazilian livestock production accounts for 8.3% of global consumption (FAO, 2015) and the sector aims to capitalise on growing demand. But related emissions are significant in the national GHG total including those related to deforestation. If both beef demand and target deforestation rates are to be met, while also reaching ambitious GHG mitigation targets, further productivity growth will be required. Alternatively product demand or consumption may need to be managed (Garnett et al., 2013; Smith, 2013).

This study focuses on the central savannah (*Cerrado*) core (Figure 5.1), an area accounting for approximately 34% of Brazilian beef production (IBGE, 2015). Considered part of the Brazilian agricultural frontier, the *Cerrado* is credited as the driver of the country's ascendance in global agricultural commodity markets (The Economist, 2010; The New York Times, 2007). Around 90% of Brazilian livestock are solely grass-fed (mainly tropical grasses of genus *Brachiaria*). Several studies show that improving tropical grasses productivity results in increased soil carbon stocks (Braz et al., 2013; Maia et al., 2009), with net atmospheric CO_2 removals of almost 1 Mg C $ha^{-1}yr^{-1}$ (Maia et al., 2009) when comparing degraded and improved pastures under a standard IPCC method (Eggleston et al., 2006).

Figure 5.1: Brazilian Central Cerrado (shaded).

The analysis quantifies the relationship between beef demand, production intensification, deforestation and soil carbon dynamics, indicating how deforestation rates influence emission intensities.

5.3 Methods

We employed a linear programming model (EAGGLE model) (Oliveira Silva, 2013) representing *Cerrado* beef production subject to market demand and pasture area scenarios . The model combines economic and bio economic variables to optimise farm resource allocation, including the adjustment of intensification levels through the representation of pasture degradation and restoration processes. It estimates GHG emissions - including direct animal emissions (Table S1), changes in SOC, plus loss of biomass through deforestation, and life-cycle assessment (LCA) data covering inputs and farm operations used to maintain and recover pasture, and crop production, the latter used to formulate animal feedlot rations (Table 3.4).

As there is no published biome-specific beef demand projections in Brazil, baseline demand (D_{BAU}) is assumed to be proportional to the whole country projected demand, i.e. exports plus domestic consumption (Gouvello et al., 2011).

We compared the accumulated emissions 2006-2030 under two land use scenarios: the Decoupled Livestock-Deforestation (DLD) scenario, where the same baseline pasture area projection (A_{BAU}) associated with the baseline demand is used for all demand scenarios; i.e., the same deforestation projections irrespective of consumption levels; and the Coupled Livestock-Deforestation (CLD) scenario, in which deforestation projections are sensitive to variations in demand. In both scenarios, intensification occurs only by pasture restoration promoting improvements in forage productivity through mechanical and chemical treatment of the soil (Table 4.2).

The varied demand scenarios are: $D_{BAU-10\%}$, $D_{BAU-20\%}$, $D_{BAU-30\%}$, representing decreasing demand/consumption scenarios relative to baseline demand by 2030, and conversely increasing demand scenarios $D_{BAU+10\%}$, $D_{BAU+20\%}$, $D_{BAU+30\%}$, (Figure 5.2a).

Deforestation is assumed exogenous, avoiding the need to model competition between livestock and agricultural land use explicitly. To explore the link between beef demand and deforestation we use a parameter (k) to represent the percentage variation of pasture area in relation to changes in demand. Based on empirical evidence (FAO, 2015; IBGE, 2015) estimated k values decreased from over 0.4 in the early 1970's to zero in the latest available data period (1995-2006), see Figure S2. In the CLD scenario we assume the worst case k = 0.4, i.e., for every 1% variation in demand, pasture area changes by 0.4%, which would generate a deforested area of 10.9 Mha by 2030 relative to 1.5 Mha for the baseline projections (Table S10).

5.4 Results

In the scenario of controlled deforestation (DLD), the analysis shows that lower than projected beef demand may increase emissions in the *Cerrado* grazing system as a result of comparatively less efficient systems with higher emission intensities. Lower demand and smaller herds require less grass production, reducing the incentive to maintain or increase productivity; pastures then degrade, losing organic matter and soil carbon stocks. Higher demand combined with effective deforestation control policies leads to more efficient systems with lower emissions intensity due to significant increases in carbon uptake by deep rooted grasses in improved pastures.

Under DLD, emissions increase by 3%, 5% and 9%, respectively for the consumption reduction scenarios $D_{BAU-10\%}$, $D_{BAU-20\%}$ and $D_{BAU-30\%}$. But in $D_{BAU+10\%}$, $D_{BAU+20\%}$ and $D_{BAU+30\%}$, emissions decrease by 3%, 7% and 10%, respectively relative to D_{BAU} (Fig. 4.2b). Increased cattle emissions in these scenarios are offset by increased grassland carbon sequestration rates. Higher annual demand leads the model to increase productivity by restoring degraded pastures, and more productive pasture is associated with a higher carbon equilibrium value (Table 3.1). Accumulated emissions (2006-2030) range from 1.9 Gt to 2.3 Gt of CO_2-e, respectively for $D_{BAU+30\%}$ and $D_{BAU-30\%}$.

But this result is undermined by altering the deforestation scenarios. Under CLD and assuming pasture expansion responds to changes in demand as in the 1970's, accumulated emissions (2006-2030) from beef production would range from 2.1 Gt to 3.0 Gt of CO_2-e, respectively for $D_{BAU-30\%}$ and $D_{BAU+30\%}$, i.e., emissions would be 60% higher than in DLD for the same demand scenario $D_{BAU+30\%}$. The analysis shows that under both $D_{BAU-10\%}$ and $D_{BAU-20\%,}$ emissions decrease by 6%. Under $D_{BAU-30\%}$ scenario emissions are reduced by 2%, relative to D_{BAU}. Under $D_{BAU+10\%}$, $D_{BAU+20\%}$ and $D_{BAU+30\%}$, emissions increase 12%, 28% and 44%, relative to D_{BAU} (Figure 5.2c). The changes are mainly due to direct animal emissions and deforestation. Note that the increasing demand scenarios drive proportional increases in deforestation, but under decreasing demand scenarios deforestation cannot be less than zero. In fact for $D_{BAU-30\%,}$ $D_{BAU-20\%}$ and $D_{BAU-10\%}$, deforestation rates are insignificant in relation to baseline figures, making GHG reductions more modest for these scenarios relative to the increases driven by deforestation under increasing demand scenarios.

Sensitivity analysis helps to identity the value of *k* representing the mid-way between CLD and DLD scenarios; i.e., the value where increases in deforestation and cattle emissions would be offset by gains from increased SOC uptake (Figure 5.2d). The analysis suggests that this offsetting occurs approximately when $k = 0.1$, i.e., only 10% of production increases are due to pasture expansion and therefore 90% due to productivity gains.

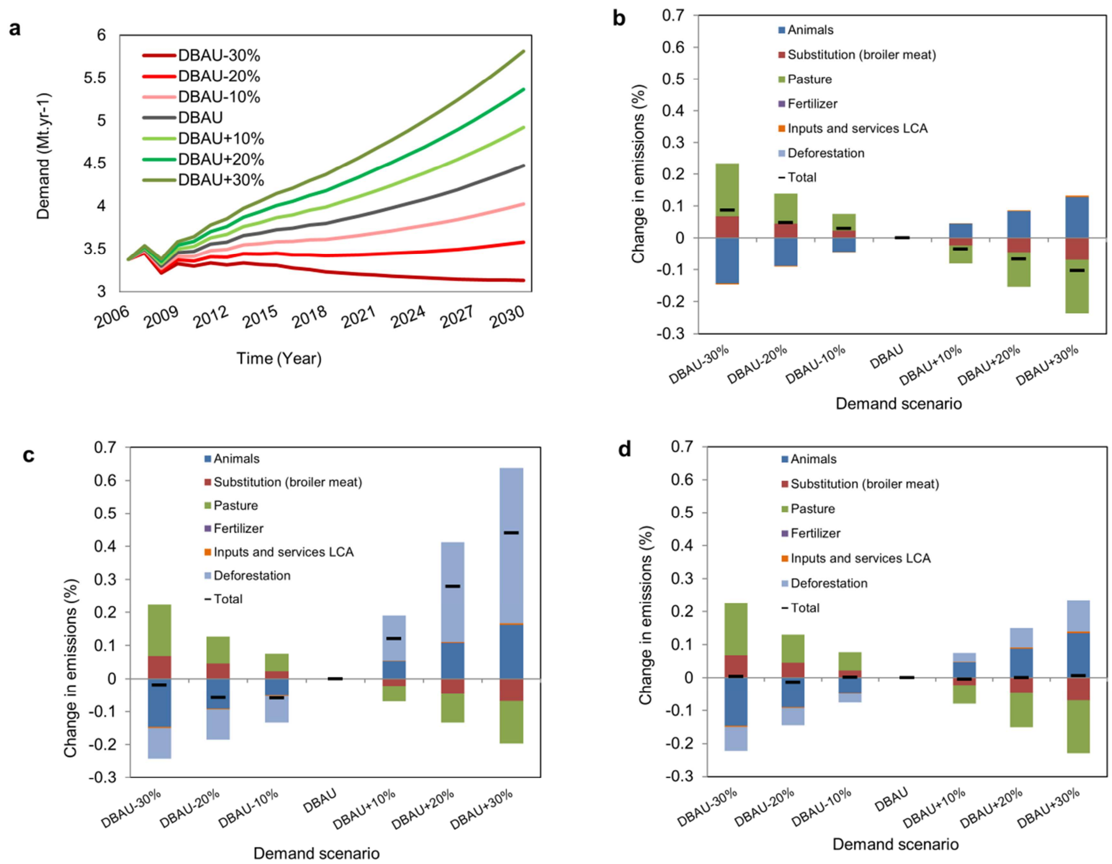


Figure 5.2: Demand scenarios and sensitivity analysis. a, Cerrado baseline demand (D_{BAU}) and varied demand projections that correspond to percentage variation by 2030 in relation to D_{BAU}, b, percentage changes in accumulated emissions (2006-2030) as a function of demand scenarios under the DLD scenario, c, changes under the CLD scenario, d, changes for k=0.1. The analysis assumes that beef consumption is substituted by broiler meat (Table S11) and accounts for the net change in production emissions arising from this substitution.

Emissions mitigation by demand-driven intensification in the DLD scenario is space and time dependent. The results depend on specific geographical data and system characteristics of *Cerrado* production, and SOC is unlikely to be accumulated indefinitely (Smith, 2014). To estimate the longevity of the inverse demand – emissions relationship (when SOC stocks approaches equilibrium content and no longer offset increased animal emissions), we conducted long-term analysis for 125 years. Assuming fixed demand from 2030 to 2130 and observing: a) the annual net emissions and b) the changes in accumulated emissions in 10 year periods from 2010 for each demand scenario under DLD. As demand projections increase up to 2030, the assumption of constant demand and area from 2030 leads to stabilized land productivity from 2030 to 2130.

Under the DLD scenario, increases in demand would lead to decreases in annual emissions up to 2057, when the situation inverts (Figure 5.3a). But Fig. 5.3b shows that in terms of accumulated emissions, reducing beef consumption would lead to decreased emissions around 2120.

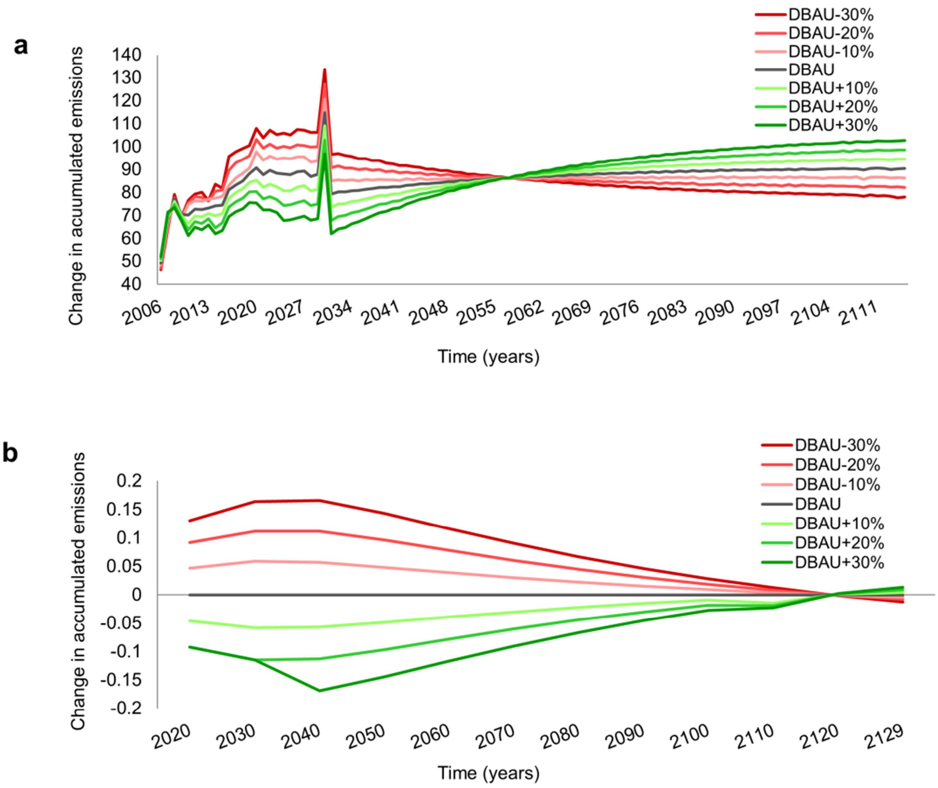


Figure 5.3: Long term GHG emissions analysis for the demand scenarios.a, annual net GHG emissions. b, percentage changes in accumulated GHGs. Note that the emissions peak in 2030 (Fig. 3a) is due to high deforestation rates in that year in the baseline projections employed[18]

Although SOC equilibrium has not been reached by 2057, the average sequestration rate of 0.08t of C.ha^{-1}.yr^{-1} (under $D_{BAU+30\%}$) no longer offsets emissions from increased animal numbers. By 2057 SOC stocks reaches 60% of the difference between initial stocks and equilibrium values, i.e., 27 years after land productivity is stabilized, which is consistent with experimental evidence. Field experiments in temperate climates suggest a period of 25 years for SOC to reach 50% of the difference between initial and equilibrium values (Johnston et al., 2009). Experiments in the Amazon report a period of 27 years to reach 60% (Nova vida site, Cerri et al. (2007)).

Our results implicitly show significant changes in emissions intensity depending on demand scenarios and deforestation. The lowest value (18.1 kg of CO_2-e/ kg of carcass equivalent (CWE) is observed under DLD and $D_{BAU+30,}$ which uses the least area to produce most beef (Figure 5.4a). Under the CLD scenario, the lowest value is found in the baseline demand (22.2 kg of CO_2-e/ kg of carcass-e), while emissions intensity could reach 31.0 kg of CO_2-e/ kg of carcass-e under $D_{BAU+30\%}$, around 40% of this being due to deforestation (Figure 5.4b).

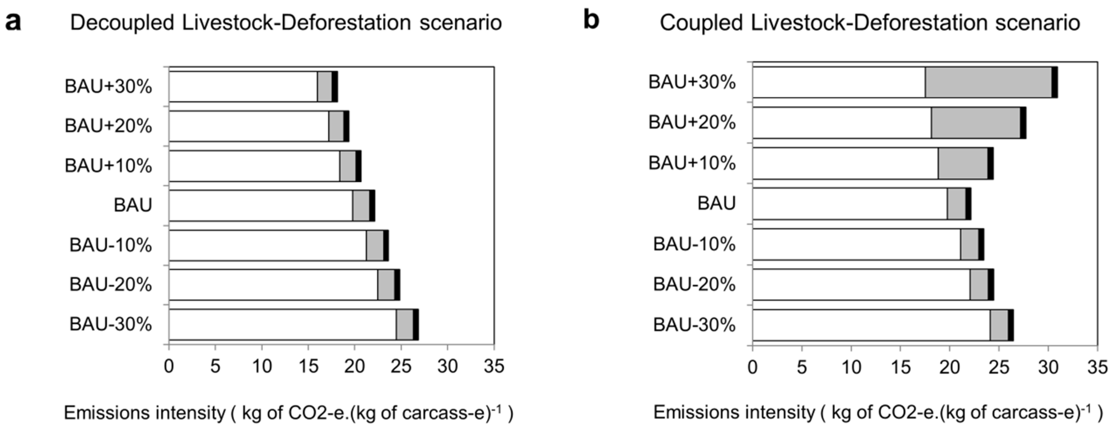


Figure 5.4: Emissions intensity as a function of demand scenario for a, Decoupled Livestock-Deforestation and b, Coupled Livestock-Deforestation land use scenarios. Carbon footprint calculated as the average value from 2010 to 2025, showing the sum of farm-emissions: animals and pasture (emissions by degradation or carbon sequestration and nitrogen fertilizers nitrification) (white),

deforestation emissions (grey) and LCA emissions from inputs and farm operations used to restore pastures and changed land use (e.g., fertilisers, seeds, and machinery operations) (black).

5.5 Discussion

The analysis contributes to the SAI debate by highlighting the potentially inverse relationship between consumption and emissions that may be found in a globally significant beef production system.

A key factor in the results is how deforestation responds to changes in beef demand (parameter *k*). In the increasingly likely scenarios of controlled deforestation, the analysis shows that lower than projected beef demand may increase emissions in the *Cerrado* grazing system due to comparatively higher emission intensities.

Empirical evidence supports the DLD scenario by showing a calibrated value of k=0 (see Figure S2). Since 2005, data show an apparent decoupling of cattle herd sizes and deforestation in Amazonia and *Cerrado*, replacing an historic correlation over the period 1975-2005; a trend attributed to a combination of supply and demand side factors including intensification in large-scale commodity-oriented farming, market regulation (e.g. moratoria on beef and soy grown in recently opened areas), product certification, and more effective law enforcement (Lapola et al., 2014; Macedo et al., 2012; Nepstad et al., 2014a).

Recent studies indicate that current global trends in livestock productivity will not accommodate future projected global demand (Bajželj et al., 2014). But this result adds to evidence that Brazil in particular has enough land to meet demand for food and energy at least until 2040 without further natural habitat conversion (Gouvello et al., 2011; Strassburg et al., 2014). In fact under DLD the highest average stocking rate in the model, 1.33 $head.ha^{-1}$ (under $D_{BAU+30\%}$), is below the 2 $head.ha^{-1}$ carrying capacity associated with negative climate impacts (Strassburg et al., 2014).

5.6 Conclusion

The analysis also indicates that restoration of degraded pastures is the biggest opportunity for national mitigation plans; indeed, after avoided deforestation, the restoration of 15 Mha nationwide from 2010 to 2020 is the main measure contributing to the 40% reduction target by 2020 (Mozzer, 2011).

Because the analysis employs consequential LCA approach (i.e., the consequential LCA approach, also called 'market based' LCA, is able to capture changes in emissions in response to changes in product demand and political decisions), it contrasts to other results (Bajželj et al., 2014; Hedenus et al., 2014; Tilman and Clark, 2014) using attributional analysis based on constant emission intensity irrespective of consumption level.

More generally our results reflect *Cerrado* system-specific data, and the picture might differ if we analyse other regions of Brazil or worldwide. The *Cerrado* is nevertheless seen as model for transforming other global savannahs (Rada, 2013).

Chapter 6 - Thesis conclusions

This thesis does not imply a comprehensive characterization of the sustainable agricultural intensification (SAI) and recognises the contested nature of the concept. The research aimed to provide mathematical examples of plausible SAI scenarios developed at a meaningful scale. I hope it partly fills a conspicuous gap in the literature, largely populated by normative conceptual papers rather than detailed models that might form policy evidence. The thesis focused on SAI measures in the Brazilian livestock context, with most attention given to the recovery of degraded pastures. To address the aforementioned literature gap I proposed a model capable of capturing the dynamics of pasture restoration, land expansion and resulting soil organic carbon changes as a function of public policies, demand and biophysical factors. Such dynamics were studied through a detailed representation of grassland degradation and intensification options (both direct and indirect pasture restoration), as in such systems a large amount of soil organic carbon can be stocked, a fact often neglected by agriculture GHG emissions studies.

The chapters address different issues but are linked in terms of demonstrating scenarios where SAI works at different scales, including supply and demand side measures. Chapter 2 develops SAI analysis at the farm scale by modelling optimal pasture management and comparing with business as usual practices to show that, provided there are financial resources for investments in intensification (own capital or access to rural credit), cattle breeders can benefit from higher returns by better decision making on pasture management.

Chapter 3 complements Chapter 2 and shows how SAI can be delivered at the regional scale. The cost-effective analyses showed that most livestock mitigation potential can be achieved by adopting win-win mitigation options, i.e., profit is increased while mitigating GHGs. It further shows that some mitigation measures currently not included in the ABC program (e.g., feed supplementation), could help the country to achieve its Nationally Appropriate Mitigation Action and Intended Nationally Determined Contributions (INDC) targets.

Chapter 4 combines the most important SAI measures (supply-side measures) identified in Chapter 3 with public polices targeting zero deforestation in Brazil. The chapter is the result of a modelling exercise commissioned by the Brazilian Ministry of Agriculture on the livestock contribution to the Brazilian INDC. This chapter addresses the trade-offs implicit in ending deforestation in Brazil by 2030 while accommodating agricultural production and therefore economic growth, and shows the extent of pasture restoration and cost-effective mitigation needed for INDC implementation.

Chapter 5 links the SAI measured in Chapter 3, policy scenarios of controlled deforestation in Chapter 4 and adds the dimension of demand-side mitigation measures. The chapter explores the link between shifting beef demand and GHG emissions. The results are counter-intuitive and show that at least in the Cerrado, reducing beef production might lead to increased GHGs, while increasing production could lead to lower emissions, provided production is decoupled from deforestation.

Much of this thesis is based on modelling through optimization techniques, which has some limitations:

Linearity: The model contains linearity assumptions, including that costs are proportional to the land area or cattle numbers. However, we used linearization techniques to represent nonlinear dynamics, e.g., pasture degradation curves and cattle weight gain.

Limitations inherent to any determinist model: All parameters are assumed to be "perfectly known". The most uncertain parameters in livestock systems in Brazil are grass seasonal productivity and cattle prices. Indeed under climate change scenarios, for time horizons of more than 100 years it is recommended to use climate models to predict scenarios of forage productivity, as productivity is expected to change as a result of increased temperature, reduced rainy season and precipitation levels in the Cerrado (M M C Bustamante et al., 2012). Another uncertainty relates to the SOC modelling. SOC accumulation (Equation 2.25) can be written as an exponential function, thus small changes in the parameter that represents C losses due to plant respiration (ρ_p) causes significant changes on SOC accumulation rates, variable $C_{t,p}$ in Equation 2.25. To resolve that problem, I calibrated equation 2.25 by finding the value of ρ_p that would mimics the CENTURY model, which has been validated for Brazilian conditions in several studies (Braz et al., 2013; Cerri et al., 2007; Maia et al., 2009).

In future I plan to include uncertainty in the most problematic the parameters by developing a stochastic programming version of EAGGLE or by using robust optimization theory.

The analysis also assumes that each biome acts like a single farm, neglecting the heterogeneity of the biomes and production systems. However, a lack of data constrains research in this area. More granular research could be developed by better information on the level of heterogeneity of production systems in each biome, defining the typical systems, structural costs, size and biophysical physiognomies. EMBRAPA recently collected this type of data and has signed research collaboration meaning that I am refining the modelling by better treatment of heterogeneity.

The analysis further assumes cattle breeders make decisions based on profit maximization, although farmers take decisions based on other criteria, such as aversion to change and risk, and cultural beliefs and what they know about neighbouring farms. Using other modelling approaches would help to address some of the questions EAGGLE cannot address, e.g., agent based modelling to investigate the barriers to technology adoption.

The effects of higher CO_2 concentration in the atmosphere on grass productivity and cattle mortality was not included in the analysis. This was due to a lack of models calibrated for Brazilian conditions, and because most of the analysis focused on a 20-25 year period, which is short for climate change effects.

The work assumed livestock production as a closed system, i.e., we did not model interactions through partial or global equilibrium modelling. In fact, demand and land availability are exogenous to our model, and the projections were generated by general equilibrium models. Although a general equilibrium model would not affect our results (at least in the range of demand change we set in the analysis), such models would allow agricultural market interactions (prices and demand).

Due to a lack of long-term experiments or chronosequences on soil organic carbon in Brazilian sites, we assumed grasslands were already in equilibrium in the first year of the analysis, meaning SOC sequestration potential from improved pasture management may be underestimated.

Further improvement of the SAI and food production nexus would benefit from the inclusion of soybeans and consideration of land competition with beef cattle, which are the biggest drivers of deforestation in Brazil. Climate change adaption studies are also required given limited existing research in Brazil. In future I aim to model climate change scenarios and adaptation measures through the inclusion of uncertainty in the parameters of the model that are sensitive to climate change. Furthermore, the inclusion of other crops and agricultural products that form Brazilian diets will allow research that addresses emissions intensity of the baseline diets in Brazil and the impact of shifting to healthier and sustainable diets.

Despite of the recent success in arresting deforestation while increasing agricultural production, the gap between current average productivity and most efficient farmers is significant and the intensification challenge is to close this gap. Agricultural intensification in Brazil will require political will and economic growth. The current political and economic crisis raises concern as to whether the sustainable intensification agenda can be followed. Beef consumption has already decreased to 32 kg of CWE per person in 2016, while the figure was around 40 in previous years (Conab, 2016). The total rural credit offered in different credit lines in Brazil amounted to 58.32 billion US$ in 2015 (20% higher than in the previous year). For 2016, the government announced a total budget of US$57.48 billion, while agricultural representative associations argue that production costs have increased. Reduced research funding is another causality of the current economic situation (Wade, 2016). Agriculture is a key sector in Brazilian economy and the country offered bold commitments at COP15 and COP21. But whether the current economic crisis will negatively affect its sustainable agenda is uncertain.

This thesis is the result of a modelling exercise of Brazilian beef systems but the results have implications for similar grazing systems elsewhere. For example, in sub-Saharan Africa, agriculture is one the most important sources of employment and income but faces similar challenges. Specifically in terms of low average productivity levels due to poor pasture management (Otte and Chilonda, 2002). Beef productivity is extremely low in traditional systems associated with low farm income and high emissions intensities, with cattle direct emissions per kg of meat roughly the double of the world's average (Opio et al., 2013). Those could be reduced by the SAI measures identified in this work, for example cattle supplementation to shorter animal life cycle and the method of partition based pasture optimization to improve forage quality while minimizing investment costs.

There is potential to extend our findings to other Latin American nations. In Colombia, livestock is a major contributor to GHG emissions (The World Bank, 2014). Around 50% of Colombian pastures are degraded and SAI has been promoted with similar measures (as Brazil), including direct pasture restoration and the integration of crop-livestock or silvopastoral system (The World Bank, 2014). The cost-effective measures identified in this work could be extended to the Colombian livestock system, given the similarities.

Furthermore, the methods I developed in Chapter 4 to accommodate agricultural growth with deforestation targets through the adoption of pasture restoration could inform similar efforts for achieving zero deforestation in Colombia. Indeed, from the estimated 36 M ha used for grazing in Colombia, 18 M ha could be freed up for alternative uses since economically feasible intensification measures are adopted (The World Bank, 2014). Finally, in this work I show how SAI could work at different scales and scenarios mostly in the Cerrado system. But the region is recognized as a potential model for other transforming other savannas (Morris et al., 2012).

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Appendix 1: Supplementary information

EAGGLE Mathematical description

List of indexes

Symbol	Description	Range/value
i,j	Land use	{A, B, C, D, E, F, Corn(silage), Corn(grain), Soybeans}
p,q	Pasture level	{A, B, C, D, E, F}
c	Crops	{Corn(silage), Corn(grain), Soybeans}
kc	Cow breeding stage	{1, 2, ... , 12}
kh	Heifer age cohort	{1, 2, ... , 9}
ks	Steer age cohort	{1, 2, ... , 9}
kp	Age cohort of protein supplemented steers	{1, 2, ... , 6}
m	Production month	{1,2,...,M}
$CM_{(m)}$	Calendar month equivalent to production month *m*	{Jan, Feb, ... , Dec}
t	Year	{1, 2, ... , T}
$t_{(m)}$	Corresponding year to the production month *m*	{1, 2, ... , T}

List of decision variables

Symbol	Description	Unit
$CASH_m$	Cash in month *m*	M R$
CIN_m	Cash incomes in month *m*	M R$
$CNIH_m$	Costs of nitrification inhibitors in month *m*	M R$
COT_m	Cash outcomes in month *m*	M R$
CSC_m	Concentrate supplementation costs in month m	M R$
CSP_m	Protein supplementation costs in month m	M R$
EDA_t	Endogenous deforestation in year *t*	M ha
FSC_m	Number of finished steers under concentrate supplementation at month *m*	M head
FSF_m	Number of steers finished under feedlot system in month *m*	M head
IC_m	Number of cows inserted in the system in month *m*	M head
$IH_{m,kh}$	Number of heifers of age cohort *kh* inserted in the system in month *m*	M head
ISC_m	Incomes from concentrate supplementation in month *m*	M R$
$IS_{m,ks}$	Number of steers of age cohort *ks* inserted in the system in month *m*	M head
ISP_m	Income from protein supplementation in month *m*	M R$
$LUC_{t,i,j}$	Land use change (or pasture restoration) from *i* to *j* in year *t*	M ha
$LU_{t,j}$	Land use *j* in year *t*	M ha
NBC_m	Number of new born calves in month *m*	M head
PC_m	Number of purchased cows in month *m*	M head
$PFFP_m$	Pasture forage intake by protein supplemented steers in month *m*	M t.(M head)$^{-1}$
$PFSC_m$	Pasture forage intake by concentrate supplemented steers in month *m*	M t.(M head)$^{-1}$
$PH_{m,kh}$	Number of purchased heifers of age cohort *kh* in month *m*	M head
PSC_t	Quantity of beef produced from concentrate supplemented steers in year *t*	M t
$PS_{m,ks}$	Number of purchased steers of age cohort *ks* in month *m*	M head

PSP_t	Amount of beef produced from protein supplemented steers in year *t*	M t
$RFSC_{m,c}$	Amount of crop *c* required for concentrate supplemented steers in month *m*	M t
$RFSP_{m,c}$	Amount of crop *c* required for protein supplemented steers in month *m*	M t
$RPA_{t,p}$	Removed area from pasture *p* in year *t*	M ha
SC_m	Number of steers supplemented with concentrate in month *m*	M head
$SCP_{m,c}$	Stored amount of crop *c* in month *m*	M t
SCV_m	Number of stocked calves in month *m*	M head
$SCW_{m,kc}$	Number of stocked cows in breeding stage *kc* in month *m*	M head
SF_m	Number of stocked steers under feedlot system in month *m*	M head
SHB_m	Number of selected heifers for breeding in month *m*	M head
$SH_{m,kh}$	Number of stocked heifers of age cohort *kh* in month *m*	M head
$SP_{m,kp}$	Number of steers of category *kp* supplemented with protein in month *m*	M head
SSC_m	Number of steers selected for concentrate supplementation in month *m*	M head
$SSF_{m,k}$	Number of steers selected to feedlot in month *m*	M head
$SS_{m,ks}$	Number of stocked steers of age cohort *ks* in month *m*	M head
SSP_m	Number of steers selected for protein supplementation in month *m*	
TDM_m	Amount of dry minter transferred from month *m* to month *m+1*	M t
UC	Used money from own capital	M R$
WC_m	Number of weaned calves in month *m*	M head

List of parameters

Symbol	Description	Unit
	General coefficients	
$A_{o,j}$	Initial area of land use *j*	M ha
BD_t	Beef demand in year t	M t
c_{ins}	Cost of insemination	$R\$.head^{-1}$
c_{salt}	Cost of mineral salt	$R\$.t^{-1}$
DA_t	Exogenous deforestation	M ha
dmi_{CV}	Dry-matter intake of calves	$Kg.head^{-1}.mth^{-1}$
dmi_{kc}	Dry-matter intake of cows of breeding stage *kc*	$Kg.head^{-1}.mth^{-1}$
dmi_{kh}	Dry-matter intake of heifers of age cohort *kh*	$Kg.head^{-1}.mth^{-1}$
dmi_{ks}	Dry-matter intake of steers of age cohort *ks*	$Kg.head^{-1}.mth^{-1}$
DM_o	Initial pasture productivity	$t.ha^{-1}$
fc	Fixed costs per pasture area	$R\$.ha^{-1}.mth^{-1}$
ir	Savings interest rate	$\%.yr^{-1}$
mc_{CV}	Maintenance cost of calves	$R\$.head^{-1}.mth^{-1}$
mch_{kh}	Maintenance cost of heifers of age cohort *kh*	$R\$.head^{-1}.mth^{-1}$
mc_{kc}	Maintenance cost of cows of breeding stage *kc*	$R\$.head^{-1}.mth^{-1}$
mcs_{ks}	Maintenance cost of steers of age cohort *ks*	$R\$.head^{-1}.mth^{-1}$
oc_{Max}	Available own capital	M R$
prc_{kc}	Price of cows in breeding stage *kc*	$R\$.head^{-1}.mth^{-1}$
prh_{kh}	Price of heifer of age cohort *kh*	$R\$.head^{-1}.mth^{-1}$
$prod_{p,CM}$	Dry-minter productivity of pasture *p* in the calendar month *CM*	$t.ha^{-1}.mth^{-1}$
prs_{ks}	Price of steers of age cohort *ks*	$R\$.head^{-1}.mth^{-1}$
tc	Cattle trading cost	$R\$.head^{-1}$
α	Adjustment parameter for the end of production	dimensionless
γ_{CC}	Cull cow carcass yield	dimensionless
γ_H	Heifer carcass yield	dimensionless
γ_S	Steer carcass yield	dimensionless
ζ	Ratio of herbage mass loss due to grazing (grazing efficiency)	dimensionless

μ_{CV}	Calf mortality rate	dimensionless
μ_{CW}	Cow mortality rate	dimensionless
μ_{kh}	Mortality rate of heifers of age cohort *kh*	dimensionless
μ_{ks}	Mortality rate of steers of age cohort *ks*	dimensionless
$\sigma_{CM(m)}$	Ratio of herbage mass loss due senescence	dimensionless
$\tau_{CM(m)}$	Minimum herbage mass (dry minter) transference in month CM(m)	$t.ha^{-1}.mth^{-1}$
ψ	Fraction of feedlot steers in relation to the total slaughtered animals	dimensionless
ω_{CC}	Weight of cull cows	kg
ω_{S}	Weight of steers finished under pasture	kg
ω_{H}	Weight of heifers finished under pasture	kg
Pasture restoration coefficients		
INAi,j	Amount applied of input (or service) *inp* on land use (or pasture restoration) from land use *i* to *j*	$kg.ha^{-1}$
$c_{i,j}$	Cost of land use change (or pasture restoration)	$R\$.ha^{-1}$
$NA_{i,j}$	Nitrogen application on land use change (or pasture restoration) from land use *i* to *j*	$kg.ha^{-1}$
Feedlot finishing coefficients		
dmi_{FL}	Dry-matter intake of feedlot steers	$Kg.head^{-1}.mth^{-1}$
nfc_{FL}	Non feed costs of feedlot finishing	$R\$.head^{-1}.mth^{-1}$
pr_{FL}	Selling price of feedlot steers	$R\$.head^{-1}.mth^{-1}$
$prr_{c,FL}$	Fraction of crop *c* in the feedlot ration composition	dimensionless
$prr_{salt,FL}$	Proportion of mineral salt in feedlot ration	%
γ_{FL}	Feedlot steer carcass yield	dimensionless
μ_{FL}	Mortality rate of feedlot steers	dimensionless
ω_{FL}	Weight of steers finished under feedlot	kg
Supplementation concentrate coefficients		
c_{urea}	Cost of mineral urea	$R\$.kg^{-1}$
dmi_{SC}	Steers' dry-matter intake of concentrate supplementation	$kg.head^{-1}.mth^{-1}$
mc_{SC}	Maintenance cost of supplemented concentrate steers	$R\$.head^{-1}.mth^{-1}$
nfc_{SC}	Non feed costs of supplementation concentrate	$R\$.head^{-1}.mth^{-1}$
$pdmi_{SC}$	Forage dry matter intake of concentrate supplemented steers	$R\$.kg^{-1}.mth^{-1}$

$prr_{c,SC}$	Proportion of crop *c* in the concentrate supplement	dimensionless
$prr_{salt,SC}$	Proportion of mineral salt in concentrate supplement	dimensionless
$prr_{Urea,SC}$	Proportion of urea in concentrate supplement	dimensionless
pr_{SC}	Selling price of steers finished under supplementation concentrate	$R\$.head^{-1}$
γ_{SC}	Carcass yield of concentrate supplemented steers	dimensionless
μ_{SC}	Mortality rate of supplemented concentrate steers	dimensionless
ω_{CS}	Finishing weight of Concentrate supplement steer	kg
Supplementation protein coefficients		
$dmi_{SP,kp}$	Dry-matter intake of concentrate supplementation of steer of age cohort *kp*	$kg.head^{-1}.mth^{-1}$
msp_{kp}	Maintenance cost of supplemented protein steer of age cohort *kp*	$R\$.head^{-1}.mth^{-1}$
nfc_{SP}	Non feed costs of supplementation protein	$R\$.head^{-1}.mth^{-1}$
$pdmi_{kp}$	Forage dry matter intake of concentrate supplemented steers of age cohort kp	$kg.head^{-1}.mth^{-1}$
$prr_{c,SP}$	Proportion of crop *c* in the protein ration	dimensionless
$prr_{NaCl,SP}$	Proportion of NaCl in protein ration	dimensionless
$prr_{salt,SP}$	Proportion of mineral salt in protein ration	dimensionless
$prr_{urea,SP}$	Proportion of urea in protein ration	dimensionless
pr_{SP}	Price of steer of age cohort *kp* supplemented with protein	$R\$.head^{-1}$
γ_{SP}	Carcass yield of protein supplemented steers	dimensionless
μ_{kp}	Mortality rate of supplemented protein steers of age cohort *kp*	dimensionless
ω_{kp}	Weight of protein supplemented steer of age cohort *kp*	kg
Nitrification inhibitors coefficients		
c_{NIH}	Cost of nitrification inhibitors	$R\$.kg^{-1}$
$cv_{N,N2O}$	Conversion factor of N into N_2O	dimensionless
p_{NIH}	Nitrification inhibitors efficiency	dimensionless
a_{NIH}	Nitrification inhibitors application (proportional to N application)	dimensionless
RL	Proportion of N saved by using nitrification inhibitors	dimensionless
GHG emissions coefficients		
ce_m	Total cattle emissions (in the baseline)	$Kg\ CO_2e.mth^{-1}$

$ce_{m,SC}$	Total cattle emissions from concentrate supplemented steers	Kg $CO_2e.mth^{-1}$
$ce_{m,SC}$	Total cattle emissions from protein supplemented steers	Kg $CO_2e.mth^{-1}$
$cs_{t,j}$	Soil organic carbon stock under land use *j* in year *t*	Mt C
$cv_{N \rightarrow N2O}$	Conversion factor of N to N_2O	dimensionless
de_t	Total natural vegetation emissions	Mt $CO_2e.yr^{-1}$
ec_{kc}	Emission factor of cow of age cohort *kh*	Kg $CO_2e.head^{-1}.mth^{-1}$
e_{CV}	Emissions factor of calves	Kg $CO_2e.head^{-1}.mth^{-1}$
e_{FL}	Emissions factor of feedlot steers	Kg $CO_2e.head^{-1}.mth^{-1}$
eh_{kh}	Emission factor of heifer of age cohort *kh*	Kg $CO_2e.head^{-1}.mth^{-1}$
es_{ks}	Emission factor of steer of age cohort *ks*	Kg $CO_2e.head^{-1}.mth^{-1}$
fe_t	Total N-based fertilizers emissions (without nitrification inhibitors)	Mt $CO_2e.yr^{-1}$
$fe_{t,NIH}$	Total N-based fertilizers emissions (with nitrification inhibitors)	Mt $CO_2e.yr^{-1}$
r	Carbon respiratory losses parameter	dimensionless
$\Delta cs_{t,j}$	Amount of carbon sequestration under land use *j* in year *t*	Mt $C.yr^{-1}$
ε_j	Carbon equilibrium stock under land use *j*	$t.ha^{-1}$
θ	Natural vegetation above ground biomass	t $C.ha^{-1}$
σ	Natural vegetation below ground biomass	t $C.ha^{-1}$

$$\text{Max } CASH_M \quad (1)$$

S.t:

$$LU_{t,j} = A_{o,j} \ \forall j \qquad (2)$$

$$LU_{t,p} = LU_{t-1,p-\partial(t)} + \sum_i (LUC_{t,i,p} - LUC_{t-1,p-\partial(t),i}) - RPA_{t,p} \qquad (3)$$
$$t > 1, \text{p} \neq \text{C}$$

$$LU_{t,p} = LU_{t-1,p-\partial(t)} + \sum_i (LUC_{t,i,p} - LUC_{t-1,p-\partial(t),i}) + DA_t + EDA_t - RPA_{t,p} \qquad (4)$$
$$t > 1, \ p = \text{C}$$

$$LU_{t,c} = \sum_i LUC_{t,i,c} \ , \quad t > 1 \qquad (5)$$

$$\sum_j LUC_{t,p,j} + RPA_{t,p} \leq LU_{t-1,p} \quad , \quad t > 1 \qquad (6)$$

$$\sum_j LUC_{t,c,j} \leq LU_{t-1,c} \quad , \quad t > 1 \qquad (7)$$

$$SS_{m,ks} = IS_{m,ks} + (1-\mu_{ks})SS_{m-1,ks} + \sum_{r}\prod_{i=1}^{r}(1-\mu_{ks-i})^{3} IS_{m-3r,ks-r} - \\ -\sum_{r}\prod_{i=1}^{r}(1-\mu_{ks+1-i})^{3} IS_{m-3r,ks-r+1} \; , \forall m \; , ks < 9 \; , \quad r \in \{1,2,...\} \qquad (8)$$

$$SS_{m,ks} = \sum_{r}\prod_{i=1}^{r}(1-\mu_{ks-i})^{3} IS_{m-3r,k-r} \; , \forall m \; , ks = 9 \; , \quad r \in \{1,2,...\} \quad (9)$$

$$IS_{m,ks} = 0.5WC_{m} + PS_{m,ks} \; , \quad \forall m, \quad ks = 1 \quad (10)$$

$$IS_{m,ks} = PS_{m,ks} - SSF_{m} \; , \quad \forall m, \quad ks = 7 \quad (11)$$

$$IS_{m,ks} = PS_{m,ks} \; , \quad \forall m, \quad ks > 1 \wedge ks \neq 7 \quad (12)$$

$$SH_{m,kh} = IH_{m,kh} + (1-\mu_{kh})SH_{m-1,ks} + \sum_{r}\prod_{i=1}^{r}(1-\mu_{ks-i})^{3} IH_{m-3r,ks-r} - \\ -\sum_{r}\prod_{i=1}^{r}(1-\mu_{kh+1-i})^{3} IH_{m-3r,kh-r+1} \; , \quad \forall m, \quad kh < 9, \quad r \in \{1,2,...\} \qquad (13)$$

$$SH_{m,kh} = \sum_{r}\prod_{i=1}^{r}(1-\mu_{kh-i})^{3} IH_{m-3r,kh-r} \; , \forall m, \quad kh = 9, \quad j \in \{1,2,...\} \quad (14)$$

$$IH_{m,kh} = 0.5WC_{m} + PH_{m,kh} \; , \quad \forall m, \quad kh = 1 \quad (15)$$

$$IH_{m,kh} = PH_{m,kh} - SHB_{m} \; , \forall m, \quad kh = 7 \quad (16)$$

$$IH_{m,kh} = PH_{m,kh} \ ,\forall m, \quad kh > 1 \wedge kh \neq 7 \quad (17)$$

$$SCW_{m,kc} = (1-\mu_{CW})SCW_{m-1,kc} + IC_m - IC_{m-9} \ ,\forall m \ , kc = 1 \quad (18)$$

$$SCW_{m,kc} = (1-\mu_{CW})^{15+18*3} \ IC_{m-(15+18*3)} \ ,\forall m \ , kc = 12 \quad (19)$$

$$\begin{aligned} SCW_{m,kc} &= (1-\mu_{CW})SCW_{m-1,kc} + (1-\mu_{CW})^{18ord(kc)} IC_{m-18ord(kc)} - \\ &-(1-\mu_{CW})^{9+18ord(kc)} IC_{m-(9+18ord(kc))} \ ,\forall m, kc \in P = \{4,7,10\} \end{aligned} \quad (20)$$

$$\begin{aligned} SCW_{m,kc} &= (1-\mu_{CW})SCW_{m-1,kc} + (1-\mu_{CW})^{9+18(ord(kc)-1)} IC_{m-(9+18(ord(kc)-1))} - \\ &-(1-\mu_{CW})^{15+18(ord(kc)-1)} IC_{m-(15+18(ord(kc)-1))} \ ,\forall m, kc \in L = \{2,5,8,11\} \end{aligned} \quad (21)$$

$$\begin{aligned} SCW_{m,kc} &= (1-\mu_{CW})SCW_{m-1,kc} + (1-\mu_{CW})^{15+18(ord(kc)-1)} IC_{m-(15+18(ord(kc)-1))} - \\ &-(1-\mu_{CW})^{18+18(ord(kc)-1)} IC_{m-(18+18(ord(kc)-1))} \ ,\forall m, kc \in N = \{3,6,9\} \end{aligned} \quad (22)$$

$$IC_m = PH_m + SHB_m \ ,\forall m \quad (23)$$

$$NBC_m = \sum_{i=0}^{3} IC_{m-(9+18i)} \ ,\forall m \quad (24)$$

$$SCV_m = (1-\mu_{CV})SCV_{m-1} + NBC_m - (1-\mu_{CV})^6 NBC_{m-6} \ ,\forall m \ (25)$$

$$WC_m = (1-\mu_{CV})^6 NBC_{m-6} \ ,\forall m \quad (26)$$

$$FSF_m = (1-\mu_{FL})^2 SSF_{m-2} \ ,\forall m \quad (27)$$

$$SF_m = (1-\mu_{FL})SF_{m-1} + SSF_m - FSF_m \ ,\forall m \ (28)$$

$$\sum_{m \mid \left\lceil \frac{m}{12} \right\rceil = t} FSF_m = \psi \left(\sum_{m \mid \left\lceil \frac{m}{12} \right\rceil = t} (SS_{m,9} + SH_{m,9} + FSF_m + SCW_{m,12}) \right), \forall t \quad (29)$$

$$(1+\xi)\left(\sum_{ks} dmi_{ks} SS_{m,ks} + \sum_{kh} dmi_{kh} SH_{m,kh} + \sum_{kc} dmi_{kc} SCW_{m,kc} + dmi_{CV} SCV_m\right) + TDM_m$$
$$= \quad (30)$$
$$\sum_p prod_{p,CM(m)} LU_{t(m),p} + (1-\sigma_{CM(m)})TDM_{m-1} \leq 0 \quad , \quad 1 < m \leq M$$

$$\tau_{CM(m)} \sum_p LU_{t,p} - TDM_m \leq 0 \ , \quad \forall m \quad (31)$$

$$SCP_{m,c} = SCP_{m-1,c} + prod_{c,CM(m)} LU_{t(m),c} - prr_{c,FL}\, dmi_{FL} SF_m \quad , \forall c, \forall m \quad (32)$$

$$\sum_{m \mid \left\lceil \frac{m}{12} \right\rceil = t} (\gamma_S \omega_S SS_{m,ks=9} + \gamma_H \omega_H SH_{m,kh=9} + \gamma_C \omega_C SCW_{m,kc=12} + \gamma_{FL} \omega_{FL} FSF_m) = BD_t \;, \forall t \quad (33)$$

$$CIN_m = prs_9 SS_{m,9} + \mathrm{prh}_9 SH_{m,9} + pr_{FL} FSF_m + prc_{12} SCW_{m,12} \;, \quad \forall m \quad (34)$$

$$\begin{aligned} COT_m = {} & fc \sum_p LU_{t,p} + \sum_{ks=1}^{8} (tc + prs_{ks}) PS_{m,ks} + \sum_{kh=1}^{8} (tc + prh_{kh}) PH_{m,kh} + (tc + prc_1) PC_m + \\ & + \sum_{ks} mcs_{ks} SS_{m,ks} + \sum_{kh} mch_{kh} SH_{m,kh} + \sum_{kc} mc_{kc} SCW_{m,ks} + mc_{CV} SCV_m + \\ & + (nfc_{FL} + c_{salt}\, prr_{salt,FL}\, dmi_{FL})(SF_m + FSF_m) + c_{ins} SHB_m + LI_m \sum_i \sum_j c_{i,j} LUC_{t(m),i,j} \quad , \forall m \end{aligned} \quad (35)$$

$$CASH_m = UC + CIN_m - COT_m \;, \; m = 1 \quad (36)$$

$$UC \le oc_{max} \quad (37)$$

$$CASH_m = CASH_{m-1} + CIN_m - COT_m \;, m > 1 \quad (38)$$

$$\begin{aligned} CASH_m = {} & CASH_{m-1} + CIN_m - COT_m - (1 + ir)^T UC + \\ & + \alpha \left(\sum_{ks=1}^{8} prs_{ks} SS_{m,ks} + \sum_{kh=1}^{8} prh_{kh} SH_{m,kh} + prc_{kc} \sum_{kc} SCW_{m,kc} \right) \quad (39) \\ & m = M \end{aligned}$$

$$FSC_m = (1-\mu_{SC})^2 SSC_{m-2} \ , \forall m \quad (40)$$

$$SC_m = (1-\mu_{SC})SC_{m-1} + SSC_m - FSC_m \ , \forall m \quad (41)$$

$$PSC_t = \sum_{m \mid \left\lceil \frac{m}{12} \right\rceil = t} \gamma_{SC} \omega_{SC} FSC_m \ , \forall t \quad (42)$$

$$CSC_m = ((c_{urea}\, prr_{urea,SC} + c_{salt}\, prr_{salt,SC})dmi_{SC} + nfc_{SC} + mc_{SC})SC_m \ , \forall m \quad (43)$$

$$ISC_m = pr_{SC} FSC_m \ , \forall m \quad (44)$$

$$PFSC_m = (1+\xi)\, pdmi_{SC} SC_m \ , \forall m \quad (45)$$

$$RFSC_{m,c} = prr_{c,SC}\, dmi_{SC}\, SC_m , \ \forall c , \forall m \quad (46)$$

$$SP_{m,kp} = (1-\mu_{kp})SP_{m-1,kp} + SSP_m - (1-\mu_{kp})^3 SSP_{m-3,kp} , \ kp = 1 , \forall m \quad (47)$$

$$SP_{m,kp} = (1-\mu_{kp})SP_{m-1,kp} + \prod_{r=1}^{kp-1}(1-\mu_r)^3 SSP_{m-3(kp-1)} - \prod_{r=1}^{kp}(1-\mu_r)^3 SSP_{m-3kp},\ kp > 1, \forall m \quad (48)$$

$$PSP_t = \sum_{m \mid \lceil \frac{m}{12} \rceil = t} \gamma_{SP}\omega_{kp} SP_{m,kp} \quad ,kp = 6\ , \forall t \quad (49)$$

$$CSP_m = (c_{urea}\,prr_{urea,SP} + c_{salt}\,prr_{salt,SP} + c_{NaCl}\,prr_{NaCl,SP})\sum_{kp} dmi_{SP,kp} SP_{m,kp} + \\ + \sum_{kp}(nfc_{SP} + msp_{kp})SP_{m,kp}\ , \forall m \quad (50)$$

$$ISP_m = pr_{kp} SP_{m,kp} \quad ,kp = 6\ , \forall m \quad (51)$$

$$PFSP_m = (1+\xi)\sum_{kp} pdmi_{kp} SP_{m,kp}\ , \forall m \quad (52)$$

$$RFSP_{m,c} = prr_{c,SP}\sum_{kp} dmi_{SP,kp} SP_{m,kp},\ \forall c, \forall m \quad (53)$$

$$CNIH_m = c_{NIH}\, a_{NIH}\, (1-RL)\sum_i \sum_j NA_{i,j}\, LUC_{t(m),i,j}\, LI_m \quad (54)$$

Objective function

Eq. 1 corresponds to the maximization of cash/income at the last month of production (month *M*), i.e., gross margin. $CASH_M$ (M R$) represents cash at the very last month (*M*) of production. Eq. 1 is equivalent to the expanded equivalent Eq. 39 .

Land use dynamics

Eq. 2 is responsible for allocating the initial land use of pastures types {*A*,*B*,*C*,*D*,*E*,*F*} and crops {*Corn(silage)*,*Corn(grain)*,*Soybeans*}. $LU_{t,j}$ (M ha) accounts for the allocated area of land use/pasture types *j* in year *t*, *Ao,j* represents the initial allocation of each land use/pasture types.

Eq. 3 represents the pasture allocation, allowing for degradation, pasture restoration and land use change decisions. As degradation was assumed to occur biannually, the binary parameter vector *δ(t)* is used as an index as follows:

$$\delta(t) = \begin{cases} 1, \text{ if } t \text{ is an odd number} \\ 0, \text{ if } t \text{ is even} \end{cases}$$

The area of pasture *p* in year *t* ($LU_{t,p}$) is given by the area of pasture *p* in the previous year *t-1* ($LU_{t-1,p}$) or the area pasture *p*-1 ($LU_{t-1,p-1}$) if *t* is a year where degradation occurs, i.e., *t* is an odd number, plus the area from other land uses/pasture types *i* to pasture *p* in year *t* ($\sum_i LUC_{t,i,p}$), less the area converted from pasture *p* to the other land uses/pasture types *i* ($\sum_i LUC_{t,p,i}$), subtracted from the area of pasture *p* removed in year *t* ($RPA_{t,p}$).

Eq. 4 is identical to Eq. 3 except for land expansion (endogenous and exogenous), which is allocated to pasture $p=C$ (due to equivalence of natural vegetation productivity with pasture level C. DA_t represents the exogenous pasture expansion and EDA_t the exogenous expansion term, i.e., extra deforestation required to meet demand in year t.

Eq. 5 expresses the crop allocation, which is a simpler dynamic than pasture: every year crops need to be planted and harvested. Eq. 5 says the area of crop c in year t is equivalent to the sum of converted (or re-planted in the case of $i=c$) area from all possible land uses to crop c ($\sum_i LUC_{t,i,c}$).

Eq. 6 and Eq. 7 are used to constrain the land use change variables according to the available area, respectively for pastures and crops. Eq. 6 says the area converted from pasture p to improved pastures (restoration) or to crops in year t, (first term in the right-hand side (RHS)), has to be no greater than the available area in the previous year t-1, i.e., $LU_{t-1,p} – RPA_{t,p}$. Eq. 7 is similar to Eq. 6 but for crops (unlike pasture, it is assumed no crop area is removed).

Grazing steer dynamics

Eq. 8 models the steer fattening until slaughter weight – represented as the transfer from age cohorts ks-1, ks-2, ks-3,… to ks. The number of steers (M heads) in the system in time step (month) m ($SS_{m,ks}$) is given by the combination of 4 terms: (i) the number of steers that were inserted in the system in that month ($IS_{m,ks}$); (ii) the number of steers ks in the previous month less the mortality rate (second term in the RHS); (iii) the number of steers that are changing from the previous age cohorts to ks (third term in the RHS), and (iv) the number of steers that are changing from ks to the next cohort $ks+1$ (fourth term in the RHS). (i) and (ii) are straightforward; (iii) is given by the number of steers that were inserted in the system as age cohort ks-1 three months before month m, plus the number inserted 6 months before as category ks-2 and so forth (every 3 months steers change to the next age cohort), i.e., $IS_{m-3,ks-}$

$_{1}$+ $IS_{m\text{-}6,ks\text{-}2}$ + $IS_{m\text{-}9,ks\text{-}3}$ + $IS_{m\text{-}12,ks\text{-}4}$ + … = $\sum_{r} IS_{m-3r,ks-r}$, the term multiplying $IS_{m\text{-}3r,ks\text{-}r}$ ($\prod_{i=1}^{r}(1-\mu_{ks-i})^{3}$) accounts for accumulated transfer rate according to mortality rate for each element in the sum (cubed because the mortality rate is a monthly value); (iv) is analogous to (iii).

Eq. 9 accounts for the number of finished steers, i.e., age cohort 9. In that cohort there is no monthly transfer from the same cohort, i.e, once a steer reach age cohort 9, it is slaughtered.

Eq. 10 accounts for the number of steers of the first age cohort inserted into the system (calves) in month *m* ($IS_{m,ks=1}$). An animal can be inserted into the grazing system by: (i) breeding: i.e., a calf is born in the system (first term in the RHS) or (ii) by being purchased (second variable on the RHS). Let WC_m be the number of newborn calves in month *m* and $PS_{m,ks}$ the number of calves purchased in that month. It is assumed half of the animals born are males and half females; thus WC_m is multiplied by 0.5.

Eq. 11 says the number of inserted steers of age cohort *ks*=7 is given by the number of purchased steers ($PS_{m,ks=7}$) less the number of steers allocated into feedlot systems (SSF_m).

Eq. 12 says that the number of inserted steers of age cohort *ks*≠7 equals the number of purchased steers.

Grazing heifer dynamics

Heifers are finished under the grazing system as occurs with steers, or selected to become cows, and thus generate calves in the system.

Let $SH_{m,kh}$ represents the number of heifer of age cohort *kh* in month *m*; $IH_{m,kh}$ the number of heifers *kh* inserted in the system in month *m*; $PH_{m,kh}$, the number of heifers purchased in month *m* and SHB_m the number of heifers selected for breeding in that month. Then Eq. 13 - 17 are respectively analogous to Eq. 8 - 12, but for heifers. Heifers cannot be moved to feedlot systems in the same way as steers, instead heifers of age cohort *kh*=7 can be selected for breeding process (variable SHB_m in Eq. 16) and then added to the cow-calf equation dynamics (Eq. 23).

Breeding dynamics

Each cow generates one calf per cycle, a cycle is composed of three breeding stages: (i) pregnant stage, (ii) lactation stage, and (ii) non-lactation stage. After four cycles, cows are removed from breeding process and slaughtered (cull cows). The cycles correspond to cow transfer from breeding stage *kc=1* up to *kc=12*:

Breeding stages

Breeding stage (*kc*)	Description	Duration (months)
1	1st pregnancy	9
2	1st lactation	6
3	1st non-lactation	3
4	2nd pregnancy	9
5	2nd lactation	6
6	2nd non-lactation	3
7	3rd pregnancy	9
8	3rd lactation	6
9	3rd non-lactation	3
10	4th pregnancy	9

11	4th lactation	6
12	4th non-lactation (cull cow)	1

As for the steer and heifer dynamics, the number of cows in the system (stocked cows) is given by the transfer of previous categories (or age cohorts).

Eq. 18 - 22 represent the transfer across the breeding stages, starting from 1st pregnancy (*kc=1*) until the last stage (*kc=12*) when cows are removed from the breeding system.

Eq. 18 says that the number of cows in the initial breeding stage (*kc*=1) in month *m* ($SCW_{m,ks}$) is given by the number of cows in stage *kc* in *m*-1, less the mortality rate μ_{CW} (first term in the RHS), plus the cows that are inserted into the breeding system in that month (IC_m), less the cows leaving stage *kc=1*, i.e., cows that entered the system 9 months before *m* (IC_{m-9}).

Eq. 19 says the number of cows in the last breeding stage ($SCW_{m,kc=12}$) is given by the number of cows inserted in the system 4 cycles before, i.e, $IC_{m-(15+18*3)}$. The first 3 cycles are comprised of 9 months of pregnancy, 6 months of lactation and 3 months resting, totaling 18 months, the last cycle does not include the resting stage, i.e., pregnancy +lactation, totaling 15 months.

Eq. 20 represents the dynamics of cows in the pregnancy breeding stages (for *kc>1*), i.e for *kc* ϵ P = {4,7,10}, where *P* is the set of indexes of cows in the pregnancy breeding stage. Here, the number of cows in month *m* ($SCW_{m,kc}$) is given by the number in the previous month less the mortality rate (first term in the RHS), plus the cows inserted in the system one cycle before for *kc*=4, two cycles before for *kc*=7 and 3 cycles before for *kc*=10, i.e., cows inserted in ord(kc)*18 months before month *m* ($IC_{m-18ord(kc)}$). The term $(1-\mu_{CW})^{18ord(kc)}$ is the accumulated mortality rate. Similarly, the number of cows moving from the pregnancy stages to the lactation stages in month *m* is equivalent the number of cows that were inserted as in the second term in the RHS, but 9 months before *m* , i.e., $IC_{m-(9+18ord(kc))}$.

Eq. 21 and 22 follow the same logic of Eq. 20 but represent the number of cows in lactation ($kc \in L = \{2,5,8,11\}$), and the number cows in non-lactation (or resting stage) ($kc \in N = \{3,9,6\}$), respectively.

Eq. 23 indicates the number of cows inserted into the breeding process in month *m* (IC_m) j given by the number of purchased (PH_m) plus the number of selected heifers (SHB_m).

Eq. 24 accounts for the number of newborn calves in month *m*. Let NBC_m be the number of births in month *m*, then NBC_m is equivalent to the number of cows inserted into the breeding system at *m-9*, (one cow generates one calf) plus the number of cows inserted *m*-18 (duration of a cycle), and so forth, until it completes 4 cycles, i.e., $\sum_{i=0}^{3} IC_{m-(9+18i)}$.

Eq. 25 accounts for the number of calves in the system. Let SCV_m be the number of calves in month *m*, it is then given by the transfer from *m-1* (first term in the RHS), plus births in *m* (NBC_m), less the births at *m-6* (NBC_{m-6}), since calves are fed by cows for 6 months, with all terms multiplied by respective monthly transfer with accumulated mortality rate, where μ_{CV} represents the monthly mortality rate for calves.

Eq. 26 gives the number of weaned calves (WC_m) in month *m*, i.e., calves born in *m-6*, multiplied by accumulated transfer with mortality rate, $(1-\mu_{CV})^6 NBC_{m-6}$. The weaned calves are then allocated half to steers $ks=1$ and half to heifers $kh=1$, respectively to Eq. 10 and Eq. 15.

Feedlot finishing

Eq. 27 accounts for the number of finished steers under the feedlot system in month m (FSF_m). Once a steer is selected for the feedlot (from ks=7), it takes two months to slaughter. FSF_m is equivalent to the number of steers removed from grazing system (SSF_m), multiplied by the two-months accumulated age cohorts transfer rate $(1-\mu_{FL})^2$, where μ_{FL} is the monthly mortality rate of feedlot steers.

Eq. 28 accounts for the number of steers in the feedlot (SF_m) - before slaughter. SF_m is given by the transfer from the previous month $(1-\mu_{FL})SF_{m-1}$, plus steers inserted into the feedlot in that month (SSF_m), less the slaughtered steers in that month (FSF_m).

Eq. 29 establishes the proportion of feedlot animals, i.e. the number of feedlot steers in year t has to be a proportion ψ of the total annual slaughtered cattle among grazing steers, feedlot steers, grazing heifers and discarded cows. $SS_{m,9}$ and $SH_{m,9}$ are the numbers of slaughtered animals (last age cohort) respectively for steers and heifers, $SCW_{m,12}$, the number of cull cows in month m. The sum over m such that $\left\lceil \frac{m}{12} \right\rceil = t$ (ceiling of m = t) is used make the sum over the months of the equivalent year, i.e., if t=1 then m ϵ {1,2,…12}, if t=2 then m ϵ {13,14,…,24} and so forth.

Forage budgeting

Eq. 30 represents the feed budgeting of all grazing cattle, i.e., the balance of demanded dry matter (terms in the left hand side (LHS)) and forage availability (terms in the RHS). Let dmi_{ks}, dmi_{kh}, dmi_{kc} and dmi_{CV} be the dry matter intake (in kg.hd^{-1}.mth^{-1}) of respectively steers of age cohort ks, heifer of age cohort kh, cows in breeding stage kc, and calves. The total demanded dry matter is given by the total consumed (the sums over the cohorts indexes). Because there is loss of dry matter due to animal grazing, a dimensionless parameter (ζ) is used to represent the dry matter losses proportional to the total dry matter consumed, therefore total consumption is multiplied by (1+ ζ). The model does not require that all available dry matter has to be consumed in a given month, i.e., part of it can be transferred to the next month by a variable representing the dry matter not consumed in month *m*, TDM_m (slack variable). In the RHS of the inequality the available dry matter in month *m* is represented. *Let* $prod_{p,CM(m)}$ be the dry matter productivity ($t.ha^{-1}.mth^{-1}$) of pasture type *p* in the calendar month *CM(m)*, thus the first term in the RHS represents the total dry matter produced in month *m*. The available dry matter not consumed in month *m*-1 is transferred to month *m*, less dry matter losses due to senescence process for the equivalent calendar month ($\sigma_{CM(m)}$).

Eq. 31 The slack variable TDM_m in Eq. 30 has to be greater than a minimum value, i.e., not all the available dry matter (organic matter above ground) can be consumed by grazing cattle. Instead, there is a lower bound for TDM_m, i.e., a minimum of dry-matter per hectare that has to be transferred from one month to another, represented by $\tau_{CM(m)}$.

Eq. 32 represents stocking of crops produced on the farm. Let $SCP_{m,c}$ be the amount of crop stocked in month *m* (M t), it is given by the stock from the previous month ($SCP_{m-1,c}$), plus the amount of crop *c* produced in month *m* (second term in the RHS), where $prodc_{,CM(m)}$ is the productivity of crop *c* in the calendar month *CM(m)* (in $t.ha^{-1}$), less the amount of crop *c* that is consumed for ration formulation for feedlot cattle (third term in the RHS), where dmi_{FL} is the ration dry matter intake ($t.hd^{-1}.mth^{-1}$) of feedlot steers and $prr_{c,FL}$ is a dimensionless parameter representing the proportion of the intake that is obtained from crop *c*, i.e., proportion of crop *c* in the ration formulation.

Beef demand

Eq. 33 is the demand constraint. Let γ_S, γ_H, γ_C and γ_{FL} represent the carcass yield of grazing finished steers, heifers, cull cows and feedlot finished steers, respectively; and ω_S, ω_H, ω_C and ω_{FL} the finishing weight of grazing steers, heifers, cull cows and feedlot finished steers

($kg.hd^{-1}$), respectively. Total produced meat is equivalent to the product of carcass yield by finished weight and number of finished animals in month m of each category (then summed over the equivalent months of each year using the celling operator ($\lceil\ \rceil$), as in Eq.29).

Cash flow

Eq. 34 represents farm incomes from the sale of finished animals. Let CIN_m be the farm incomes in month m, prs_9, prh_9, pr_{FL} and prc_{12} be the selling prices of finished grazing steers, heifers, finished feedlot steers and cull cows ($R\$.hd^{-1}$), respectively. Income is the product of cattle selling prices times the number of finished cattle, i.e., finished steers in month m ($SS_{m,9}$), heifers ($SH_{m,9}$), feedlot steers (FSF_m) and culled cows ($SCW_{m,12}$).

Eq. 35 represents the costs of the farm in month m (COT_m), composed of: (i) fixed costs per pasture area (first term in the RHS), where fc is the cost per hectare, multiplied by the total area in year t ($\sum_p LU_{t,p}$); (ii) cost of purchasing animals, i.e, price and transactions costs (second to fourth term in the RHS), where prs_{ks}, prh_{kh} and $prc_{kc=1}$ are the purchasing price of steers of age cohort ks, heifers of age cohort kh and cows in breeding stage kc=1, ($R\$.hd^{-1}$)respectively; tc is a parameter representing the transaction cost per head. The summations ranges from 1 to 8 because ks=9 or kh=9 correspond to finished cattle; (iii) grazing cattle maintenance costs (from fifth to eighth term in the RHS), where mcs_{ks}, mch_{kh}, mc_{kc} and mc_{CV} are the maintenance costs per head for steers, heifers, cows and calves, respectively; (iv) feedlot non-feed costs (ninth term in the RHS), where nfc_{FL} is the maintenance cost for feedlot animals ($R\$.hd^{-1}$); c_{salt} is the cost of mineral salt used in ration formulation; $prr_{salt,FL}$ is a dimensionless parameter that represents the proportion of salt in the feedlot ration composition; (v) cost of inseminating heifers (tenth term in the RHS), where c_{ins} is the insemination cost per head; (vi) land use change and pasture restoration costs (last term in the RHS), where $c_{i,j}$ is the cost to restore one hectare of pasture i to improved pasture j (or the cost of changing one hectare from land use i to j). The land use change/restoration cost is always discounted in the first month for every year by using a binary parameter LI_m, where $LI_m = 1$ if m=*January*, otherwise $m=0$.

Eq. 36 says the cash ($CASH_{m=1}$) in the first production month consists of own used capital (*UC*) plus incomes, less costs.

Eq. 37 sets a constraint on used own capital availability, where oc_{max} is the available own capital.

Eq. 38 says the subsequent monthly cash ($CASH_m$) (except the last month) is given by disposable cash from the previous month, plus incomes less costs.

Eq. 39 represents the cash in the last month *M* (equivalent to gross margin). (39) is similar to (38), but in the last month of production the model has to pay for the used capital *UC*, with a discount rate (*ir*) accumulated for *T* years (fourth term in the RHS). The last term in RHS represents the sale of the remaining animals in the system; i.e., the animals that did not achieve slaughter weight by the end of production. In this case, to avoid distortions in the solution, a calibration parameter α is used, this was determined such that the stocking rate kept approximately constant until the end of production (for fixed demand).

Concentrate supplementation

Eqs. 40 to 46 describe the supplementation concentrate measure, i.e., steer dynamics, intake and formulation of the supplement.

Eqs. 40 and 41 are analogous to eq. 27 and 28, but for concentrate-supplemented steers, where FSC_m accounts for the number of steers finished under supplementation concentrate in month *m*; μ_{SC} is the mortality rate of steers supplemented with concentrate; SSC_m represents the number of steers selected for concentrate supplementation (from age cohort $ks=8$); SC_m is the number of steers under concentrate supplementation in month m.

Eq. 42 accounts for the beef produced under concentrate supplementation during year t (PSC_t): it is derived as the product of the number of steers times the finishing weight and carcass yield. Where γ_{SC} and ω_{SC} are the carcass yield and weight of steers finished under concentrate supplementation, respectively.

Eq. 43 represents the monthly costs of concentrate supplementation (CSC_m). The cost is proportional to the number of supplemented steers in month m (SC_m) and comprises the cost of mineral salt and urea contained in the supplement (term multiplying dmi_{SC}), where c_{urea} and c_{salt} represent the cost per kg of urea and mineral salt, respectively; dmi_{SC} is the dry matter supplement consumption (kg.hd^{-1}.mth^{-1}); nfc_{SC} and mc_{SC} are non-feed costs and animal maintenance costs from concentrate supplementation (R\$.hd^{-1}.hd^{-1}.mth^{-1}).

Eq. 44 expresses the income originating from concentrate supplemented steers (ISC_m), where pr_{SC} is the selling price of concentrated steers.

Eq. 45 accounts for the forage intake of concentrate supplemented steers in month m ($PFSC_m$), where $pdmi_{SC}$ is the grass dry matter intake of concentrate supplemented steers (in t.hd^{-1}.mth^{-1}).

Eq. 46 accounts for all the dry matter consumed from each crop contained in the concentrate supplement formulation in month m ($RFSC_{m,c}$), where $prr_{c,SC}$ is a dimensionless parameter that represents the proportion of crop c contained in concentrate formulation and dmi_{SC} is the concentrate dry matter intake (in t.hd^{-1}.mth^{-1}).

Protein supplementation

Eq. 47-54 describes the protein supplementation dynamics.

Eq. 47 represents the number of steers in the first age cohort of the category of protein supplemented steers. The number of steers for $kp=1$ in month m ($SP_{m,kp=1}$) is given by the number in $m-1$($SP_{m-1,kp=1}$) less the mortality rate (first term in the RHS), where μ_{kp} is the mortality rate for protein supplemented steers of age cohort kp, plus the animals selected to be fed by protein supplementation in month m (SSP_m, selected from ks=1), less the steers transferred to the next age cohort – after 3 months (third term in the RHS).

Eq. 48 is similar to eq. 47 but accounts for $kp>1$. The number of steers that are changing to age cohort kp in month m (second term in RHS) is given by the number of steers selected for protein supplementation 3 months before, plus the steers selected 6 months before, 9 months before and so on $= (1-\mu_{kp=1})^3 SSP_{m-3} + (1-\mu_{kp=1})^3 (1-\mu_{kp=2})^3 SSP_{m-6} + (1-\mu_{kp=1})^3 (1-\mu_{kp=2})^3 (1-\mu_{kp=3})^3 SSP_{m-9} = \prod_{r=1}^{kp-1} (1-\mu_r)^3 SSP_{m-3(kp-1)}$. The third term in RHS is analogous but account for the number of steers that are changing from kp to the next age cohort kp+1.

Eqs. 49-53 are analogous to eq. 42-46, respectively. Where PSP_t is the meat produced from finished protein supplemented steers; γ_{SP} and ω_{SP} are the carcass yield and weight of finished protein supplemented steers, respectively; $SP_{m,kp}$ the number of steers under that supplementation in month m; CSP_m the monthly total cost of supplementing steers with protein, where $prr_{urea,SP}$, $prr_{salt,SP}$ and $prr_{NaCl,SP}$ are the proportion of urea, mineral salt and NaCl contained in protein supplement formulation, respectively; $dmi_{SP,kp}$ is the protein supplementation consumed of steers age cohort kp (t.hd^{-1}.mth^{-1}); nfc_{SP} and msp_{kp} are non-feed and maintenance costs for supplemented steers of age cohort kp (R\$.hd^{-1}.mth^{-1}); pr_{kp} is selling price of steers finished under protein supplementation (note that kp=6 is the finishing age cohort); and $pdmi_{kp}$ is the grass dry matter intake of steers age cohort kp.

Nitrification inhibitors

Eq. 54 expresses the monthly costs of nitrification inhibitors ($CNIH_m$) – proportional to applied nitrogen. Let c_{NIH} be the cost of the kg nitrification inhibitor; a_{NIH} a dimensionless parameter representing application (kg of inhibitor per kg of N); RL is the proportion of N saved by using nitrification inhibitors (dimensionless); and $NA_{i,j}$ is the amount of N applied to convert one hectare of land use *i* to land use *j*. Thus, the double summations over *i* and *j* account for all the applied N in year *t*; LI_m (as in Eq. 35) is used to discount the costs in the first month for every year ($LI_m = 1$ if $m=January$, otherwise $m=0$).

GHG emissions accounting

Cattle emissions

The equations below account for direct GHG emissions from cattle by employing emissions factors.

$$ce_m = \sum_{ks} es_{ks} SS_{m,ks} + \sum_{kh} eh_{kh} SH_{m,kh} + \sum_{ks} ec_{kc} SCW_{m,kc} + e_{CV} SCV_m + e_{FL} (SF_m + FSF_m), \forall m \quad (55)$$

$$ce_{m,SC} = e_{SC} SC_m , \forall m \quad (56)$$

$$ce_{m,SP} = \sum_{kp} e_{kp} SP_{m,kp} , \forall m \quad (57)$$

Eq. 55 accounts for the greenhouse gases emissions (in CO_2e) for each cattle age cohort and feedlot steers, where ce_m is the total cattle emissions in month *m*; es_{ks}, eh_{kh}, ec_{kc} and e_{FL} are the emissions factors (in kg of $CO_2e.hd^{-1}.mth^{-1}$) for steers of age cohort *ks*, heifers of age cohort *kh*, cows in breeding stage *kc* and feedlot steers, respectively.

Eq. 56 and eq. 57 account for concentrate and protein supplemented steer emissions, respectively, where e_{SC} and e_{kp} are the emissions factors (kg of $CO_2e.hd^{-1}.mth^{-1}$) of steers supplemented with concentrate and steers supplemented with protein, age cohort *kp*.

Fertilization emissions

$$fe_t = 298 cv_{N \to N_2O} \sum_j \sum_j NA_{i,j} LUC_{t(m),i,j} \quad (58)$$

$$fe_{t,NIH} = (1 - p_{NIH}) fe_t \quad (59)$$

Eq. 58 accounts for the emissions from nitrogen (N) based fertilizers in year *t* (fe_t). The term inside the sum gives the amount of N applied for all land use and pasture restoration options. The factor $cv_{N \to N2O}$ corresponds to the proportion of N converted into N_2O; and 298 is the N_2O equivalence in CO_2e - in global warming potential for 100 years (GWP-100).

Eq. 59 accounts for the emissions from N-based fertilizers when nitrogen inhibitors are used, where in p_{NIH} represents the efficiency of nitrification inhibitors .

Deforestation emissions

$$de_t = \frac{11}{3}\theta(EDA_t + DA_t) \qquad (60)$$

Eq. 60 accounts for emissions from natural vegetation conversion into pastures in year t (de_t), where EDA_t and DA_t represent the endogenous and exogenous deforested area. Emissions are given by the product of the deforested area multiplied by biomass above ground coefficient, θ (in carbon per unit of area), converted to CO_2e by multiplying by 11/3.

Pasture emissions and carbon sequestration

The equations below describe the pasture soil carbon dynamics.

$$cs_{t,p} = cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} RPA_{t,p} + \qquad (61)$$
$$+ \Delta cs_{t,p} \;, \forall t,\; p \neq \mathrm{C}$$

$$\Delta cs_{t,p} = r\left(\varepsilon_p - \left(cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \right.\right.$$
$$\left.\left. - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} RPA_{t,p} \right)\right) LU_{t,p} \qquad (62)$$
$$\forall t,\; p \neq \mathrm{C}$$

$$cs_{t,p} = cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} RPA_{t,p} + \\ + \sigma\left(EDA_t + DA_t\right) + \Delta cs_{t,p} \ , \forall t, p = \mathrm{C} \quad (63)$$

$$\Delta cs_{t,p} = r\left(\varepsilon_p - \left(cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \\ - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} LUC_{t,p} + \sigma\left(EDA_t + DA_t\right) \right)\right) LU_{t,p} \quad (64) \\ \forall t, p = \mathrm{C}$$

$$cs_{t,c} = \sum_i \frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,c} + r\left(\varepsilon_c - \sum_i \frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,c} \right) LU_{t,c} \quad (65) \\ \forall t, \forall c$$

Eq. 61 describes the soil carbon accumulation for pastures levels except pasture $p=C$.

The amount of stocked carbon under pasture p in year t ($cs_{t,p}$) (in tonnes of carbon) is given by the carbon transferred from pasture $p-1$ (degradation) or the carbon transferred from pasture p itself, if no degradation occurs (first term in the RHS), as in Eq. 3. The second term in the RHS represents the transferred carbon from/to any other pasture or crops according to the land use change decision variables. We assume a proportional transfer of carbon per area of converted land use, e.g., if 100 ha of pasture F is restored to pasture A in year t, then the carbon in F has to be proportionally transferred to A, i.e., the amount of carbon per unit of area in F in $t\text{-}1$ $\left(\dfrac{cs_{t-1,F}}{LU_{t-1,F}}\right)$ multiplied by $LUC_{t,F,A}$ = 100 ha is transferred to pasture A. The second term inside the sum is analogous but accounts for the carbon that is transferred from pasture p to other improved pasture or crops. The third term in RHS is responsible for removing carbon when pasture area ($RPA_{t,p}$) is removed from pasture level p in year t. The last term on the RHS represents the carbon sequestration rate.

Eq. 62 describes the carbon sequestration rate under pasture p in year t ($\Delta cs_{t,p}$), it is calculated as a function of the difference of the current carbon stock from the carbon equilibrium value of pasture p (ε_p) (in $t.ha^{-1}$) . The parameter r represents the carbon losses by plant respiration and determines the speed in which equilibrium is reached. For simplicity, Eq. 62 can be written as $\Delta cs_{t,p} = r(\varepsilon_p - \varphi_{t,p})LU_{t,p}$, where:

$$\varphi_{t,p} = cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} RPA_{t,p} \quad \text{(62b)}$$

Eq. 62b represents the carbon stocks in pasture p in year t just before carbon sequestration occurs, i.e., the amount of carbon transferred to pasture p in year t from pasture p in t-1 or other land uses.

Eq. 63 and 64 are analogous to Eq. 61 and 62, respectively, but since for $p=C$ there is area converted from natural vegetation (EDA_t+DA_t), the carbon (assumed in equilibrium) from natural vegetation has to be transferred to pasture C as well (fourth term in the RHS of Eq. 63), where σ represents the soil organic carbon in equilibrium of natural vegetation ($t.ha^{-1}$).

Eq. 65 accounts for the soil organic carbon under crops ($cs_{t,c}$). As crops have to be planted every year, the stocked carbon is given by the transferred carbon from the previous land use, plus the sequestration rate. Analogous to the pasture sequestration rate, it is calculated as the difference between the current stock and equilibrium (ε_c), multiplied by the plant carbon respiratory losses.

Calculation of restoration and land use change costs and model calibration

We assume the cost – and therefore inputs - necessary to change from *X* to *Y*, where *X* and *Y* can be any element in *LU = {A, B, C, D, E, F, Corn(silage), Corn(grain), Soybeans}* is given by:

$$Cost(X,Y) = Cost(F,Y) - Cost(F,X)$$

The *Cost(F,Y)*, and the description and amount of inputs, for any *Y* in *LU* is presented in Table S3-S7.

In the case where *X* = *Y*, "the cost to restore from *X* to *X*", represents the cost of maintaining the DMP X, i.e., avoiding degradation. The amount of input and cost to keep any DMP level is described in Table S4.

The inputs used for the pasture restoration and plantation of corn and soybeans followed recommendations in Sousa and Lobato (2004) and Tomé Junior (1997). Machinery and services were added following technical recommendations established by Agronomists (MSc. Paulo Roberto Albertini and Dr. Luis Gustavo Barioni, Personal Communication, Campinas, 2013) and by Veterinary (Dr. Tiago Zanett Albertini, Personal Communication, Campinas, 2013), with expertise in livestock and crop systems of production in the *Cerrado* biome. Further, item prices were based on time series collected from the Institute of Agricultural Economics (IEA, 2012) and were deflated to the 2012 value using IGP-DI (FGV, 2012).

Model calibration

This section describes the process used to obtain the pasture Average Dry Matter Productivity (ADMP) from 2006, as used in the construction of the baseline scenario (section 2.5). The land use changes dynamically as a function of time (composition of the total land across the pastures types and crops), as well as the herd dynamic (composition of animals age cohorts). However, after several years, the solution tends to reach equilibrium; i.e., land and herd composition tends to present similar values throughout the simulation. To obtain the ADMP for 2006, we ran the model with the 2006 pasture area and beef demand constant for 25 years of simulation. As the solution stabilized, we calculated the ADMP as a function of the composition of pasture types for the stabilized solution and the values of DMP in Table 3.1, obtaining the value of 10 t-DM.ha^{-1}.yr^{-1}.

Supplementary Tables

Table S1: Animals categories, Dry Mater Intake (DMI), average shrunk body weight (Avg SBW) and emissions factors*

Age cohort	Age, months	Mortality rate[1] (%.mth^{-1})	Avg SBW[2], kg	DMI[3], kg.day^{-1}	CH_4[4], kg.head^{-1}.mth^{-1}	N_2O[5], kg.head^{-1}.mth^{-1}	Price[6] (US$2012.head^{-1})	Maintenance Cost[7] (US$2012.head^{-1}.mth^{-1})
Nellore Steer								
1	[6,9)	0.42	189	5.18	3.35	0.013	337.1	0.9
2	[9,12)	0.42	222	5.84	3.78	0.015	353.9	1.0
3	[12,15)	0.2	255	6.48	4.19	0.017	410.7	1.1
4	[15,18)	0.2	289	7.12	4.6	0.018	467.6	1.2
5	[18,21)	0.2	322	7.72	4.99	0.020	534.7	1.3
6	[21,24)	0.2	355	8.30	5.37	0.021	592.7	1.4
7	[24,27)	0.03	388	8.88	5.74	0.023	650.6	1.6
8	[27,30)	0.03	421	9.44	6.1	0.024	722.2	1.7
9	33	0.03	454	9.99	6.46	0.026	781.3	1.8
Nellore Heifer								
1	[6,9)	0.06	156	4.42	2.86	0.011	327.1	0.8
2	[9,12)	0.06	183	4.98	3.22	0.013	320.7	1.0
3	[12,15)	0.06	210	5.52	3.57	0.014	388.2	0.7
4	[15,18)	0.06	237	6.05	3.91	0.016	409.4	1.8
5	[18,21)	0.06	264	6.56	4.24	0.017	505.3	1.5
6	[21,24)	0.06	291	7.05	4.56	0.018	531.4	1.3
7	[24,27)	0.06	318	7.54	4.87	0.019	558.5	1.9
8	[27,30)	0.06	345	8.01	5.18	0.021	584.8	1.3
9	33	0.06	372	8.48	5.48	0.022	584.8	1.3
Nellore Cows and Cals								
Lactation	[24,96]	0.06	450	10.85	7.02	0.027	522.5	1.9
Pregnant	[24,96]	0.06	450	7.69	4.97	0.022	578.6	5.2
Non-lactation	[24,96]	0.06	400	6.48	4.19	0.020	522.5	1.9
Calf	[0,6)	0.49	36	1.03	0	0.000	-	0.8
Feedlot Nellore Steers								

FL	[21,24]	0.03	441	11.42	11.42	83.18	837.1	11.5

[1] According to Arruda and Corrêa (1992)

[2] As proposed by Costa et al. (2005)

[3] According to NRC (1996)

[4,5] Calculated following tier 2 methodology (Eggleston et. al, 2006).

[6] Prices were based on time series collected from the Institute of Agricultural Economics (IEA, 2013) and were deflated to 2012 values using IGP-DI (FGV, 2012).

[7] Provided by Agronomists (MSc. Paulo Roberto Albertini and Dr. Luis Gustavo Barioni, Personal Communication, Campinas, 2013) and by Veterinary (Dr. Tiago Zanett Albertini, Personal Communication, Campinas, 2013) with expertise in livestock and crop systems of production in the Cerrado Biome.

[*] Note that for Avg SBW, DMI and emissions factors, specific digestible dry matter values are used.

Table S2: Supplemented steers (age cohort), DM intake, weight, and emissions factors

Age cohort[1]	Age, months	Death rate[2] (%.mth^{-1})	Avg SBW[3] (kg)	DMI[4], kg.day^{-1} (supplement)	DMI[5], kg.day^{-1} (Pasture)	CH_4[6], kg.head^{-1}.mth^{-1}	N_2O[7], kg.head^{-1}.mth^{-1}	Price[8] (\$2012.head^{-1})	Maintenance Cost[9] (\$2012.head^{-1}.mth^{-1})
Contentrate supplementation									
SC	[27,32]	0.03	457	3.0	12.9	5.8	0.037	837.1	2.3
SP	Protein supplementation								
1	[6,9)	0.42	207	0.33	5.9	2.6	0.017	337.9	1.2
2	[9,12)	0.2	266	0.33	7.2	3.2	0.020	435.2	1.4
3	[12,15)	0.2	331	0.00	9.2	4.1	0.025	563.2	1.7
4	[15,18)	0.03	397	0.00	9.9	4.4	0.028	665.6	2.0
5	[18,21)	0.03	451	0.64	8.9	4.0	0.027	778.2	2.3
6	[21,24)	0.03	481	0.77	8.4	3.8	0.027	829.4	2.4

[1] SC = concentrate supplementation; SP protein supplementation

[2] According to Arruda and Corrêa (1992)

[3] As proposed by Costa et al. (2005)

[4,5] According to NRC (2000)

[6,7] Calculated following tier 2 methodology (Eggleston et. al, 2006)

[8] Prices were based on time series collected from the Institute of Agricultural Economics (IEA, 2013) and were deflated to 2012 values using IGP-DI (FGV, 2012).

[9] Provided by Agronomists (MSc. Paulo Roberto Albertini and Dr. Luis Gustavo Barioni, Personal Communication, Campinas, 2013) and by Veterinary (Dr. Tiago Zanett Albertini, Personal Communication, Campinas, 2013) with expertise in livestock and crop systems of production in the Cerrado Biome.

Table S3:Amount of inputs and costs of pasture restoration

	inputs	Quantity ($t.ha^{-1}$)	Unit cost (US$2012.$t^{-1}$)	Cost (US$2012.$ha^{-1}$)
From F to A	Dolomic limestone	3.50	26.94	94.30
	Calcium carbonate	1.00	21.76	21.76
	Fertilizer, Single Phosphate, N.P.K. 00.18.00	0.31	467.15	144.82
	Fertilizer, Potassium chloride, KCl 00.00.60 GR ST S	0.07	688.64	48.20
	Urea	0.29	688.64	199.71
	Micronutrients, FTE BR 12	0.03	563.20	16.90
	Seeds (Brachiaria brizantha cv. Marandu)	0.01	4608.00	46.08
	Machinary/Services	Quantity (hour·ha^{-1})	Unit cost (US$2012.$hour^{-1}$)	Cost (US$2012.$ha^{-1}$)
	Calcium carbonate distribution	0.50	56.32	28.16
	Calcium carbonate distribution	1.81	28.16	50.97
	Limestone distribution	1.00	28.16	28.16
	Mower drag operation, discs: 26 to 28"	0.80	35.84	28.67
	Heavy harrow disc operation, discs: 32 to 36"	0.60	35.84	21.50
	Heavy harrow disc operation, discs: 22"	0.80	25.60	20.48
	Fertilization and pasture planting	0.30	12.29	3.69
	Urea distribution	0.30	23.04	6.91
	Mechanical pasture mowing	0.12	12.80	1.54
	Internal transport	0.30	17.41	5.22
Total cost (US$2012.$ha^{-1}$)				767.07
	inputs	Quantity ($t.ha^{-1}$)	Unit cost (US$2012.$t^{-1}$)	Cost (US$2012.$ha^{-1}$)
From F to B	Dolomic limestone	3.50	26.94	94.30
	Calcium carbonate	1.00	21.76	21.76
	Fertilizer, Single Phosphate, N.P.K. 00.18.00	0.31	467.15	144.82
	Urea	0.15	688.64	103.30
	Micronutrients, FTE BR 12	0.03	563.20	16.90

	Seeds (Brachiaria brizantha cv. Marandu)	0.01	4608.00	46.08
	Machinary/Services	Quantity (hour.ha^{-1})	Unit cost (US$2012.hour^{-1})	Cost (US$2012.ha^{-1})
	Calcium carbonate distribution	0.50	56.32	28.16
	Calcium carbonate distribution	0.50	28.16	14.08
	Limestone distribution	1.00	28.16	28.16
	Mower drag operation, discs: 26 to 28"	0.80	35.84	28.67
	Heavy harrow disc operation, discs: 32 to 36"	0.60	35.84	21.50
	Heavy harrow disc operation, discs: 22"	0.80	25.60	20.48
	Fertilizer distribution and pasture planting	0.36	12.29	4.42
	Urea distribution	1.62	23.04	37.32
	Mechanical pasture mowing	0.14	12.80	1.79
	Internal transport	0.30	17.41	5.22
Total cost (US$2012.ha^{-1})				616.97
	inputs	Quantity (t.ha^{-1})	Unit cost (US$2012.t^{-1})	Cost (US$2012.ha^{-1})
From F to C	Dolomic limestone	3.50	26.94	94.30
	Fertilizer, Single Phosphate, N.P.K. 00.18.00	0.17	467.15	77.55
	Seeds (Brachiaria brizantha cv. Marandu)	0.01	4608.00	46.08
	Machinary/Services	Quantity (hour.ha^{-1})	Unit cost (US$2012.hour^{-1})	Cost (US$2012.ha^{-1})
	Calcium carbonate distribution	0.50	56.32	28.16
	Limestone distribution	1.00	28.16	28.16
	Mower drag operation, discs: 26 to 28"	0.80	35.84	28.67
	Heavy harrow disc operation, discs: 32 to 36"	0.60	35.84	21.50
	Heavy harrow disc operation, discs: 22"	0.80	25.60	20.48
	Fertilizer distribution and pasture planting	0.30	12.29	3.69
	Urea distribution	0.36	23.04	8.36
	Mechanical pasture mowing	0.43	12.80	5.50
	Internal transport	0.30	17.41	5.22

Total cost (US$2012.ha-1)				367.68
	inputs	Quantity (t.ha^{-1})	Unit cost (US$2012.t^{-1})	Cost (US$2012.ha^{-1})
	Dolomic limestone	3.77	26.94	101.57
	Fertilizer, Single Phosphate, N.P.K. 00.18.00	0.00	467.15	1.87
	Machinary/Services	Quantity (hour.ha^{-1})	Unit cost (US$2012.hour^{-1})	Cost (US$2012.ha^{-1})
From F to D	Limestone distribution	1.00	28.16	28.16
	Internal transport	0.30	17.41	5.22
	Fertilizer distribution	0.07	23.04	1.50
	Mechanical pasture mowing	0.22	12.80	2.82
Total cost (US$2012.ha^{-1})				103.44
	Machinary/Services	Quantity (hour.ha^{-1})	Unit cost (US$2012.hour^{-1})	Cost (US$2012.ha^{-1})
From F to E	Limestone distribution	1.20	28.16	33.79
	Mechanical pasture mowing	0.68	12.80	8.64
Total cost (US$2012.ha^{-1})				42.43

Table S4:Amount of inputs and costs of pasture maintenance

	inputs	Quantity ($t.ha^{-1}$)	Unit cost ($US\$2012.t^{-1}$)	Cost ($US\$2012.ha^{-1}$)
A	Fertilizer, Single Phosphate, N.P.K. 00.18.00	0.01	467.15	4.67
	Fertilizer, Potassium chloride, KCl 00.00.60 GR ST S	0.01	688.64	6.89
	Urea	0.10	688.64	66.28
	Machinary/Services	Quantity ($hour^{.}ha^{-1}$)	Unit cost ($US\$2012.hour^{-1}$)	Cost ($US\$2012.ha^{-1}$)
	Urea distribution	1.24	23.04	28.52
	Fertilizer distribution	0.12	23.04	2.86
	Mechanical pasture mowing	0.13	25.60	3.20
Total cost ($US\$2012.ha^{-1}$)				112.4
B	inputs	Quantity ($t.ha^{-1}$)		
	Fertilizer, Single Phosphate, N.P.K. 00.18.00	0.01	467.15	4.67
	Fertilizer, Potassium chloride, KCl 00.00.60 GR ST S	0.00	688.64	0.00
	Urea	0.05	688.64	33.14
	Machinary/Services	Quantity ($hour^{.}ha^{-1}$)	Unit cost ($US\$2012.hour^{-1}$)	Cost ($US\$2012.ha^{-1}$)
	Urea distribution	1.31	23.04	30.24
	Fertilizer distribution	0.06	23.04	1.44
	Mechanical pasture mowing	0.13	25.60	3.20
Total cost ($US\$2012.ha^{-1}$)				72.7

C	inputs	Quantity ($t.ha^{-1}$)	Unit cost (US$2012.t-1)	Cost (US$2012.$ha^{-1}$)
	Fertilizer, Single Phosphate, N.P.K. 00.18.00	0.01	467.15	2.34
	Machinary/Services	Quantity ($hour^{.}ha^{-1}$)	Unit cost (US$2012.$hour^{-1}$)	Cost (US$2012.$ha^{-1}$)
	Urea distribution	0.06	23.04	1.44
	Mechanical pasture mowing	0.22	25.60	5.60
Total cost (US$2012.$ha^{-1}$)				9.4
D	inputs	Quantity ($t.ha^{-1}$)	Unit cost (US$2012.$t^{-1}$)	Cost (US$2012.$ha^{-1}$)
	Fertilizer, Single Phosphate, N.P.K. 00.18.00	0.01	467.15	2.34
	Machinary/Services	Quantity ($hour^{.}ha^{-1}$)	Unit cost (US$2012.$hour^{-1}$)	Cost (US$2012.$ha^{-1}$)
	Urea distribution	0.06	23.04	1.44
	Mechanical pasture mowing	0.22	25.60	5.60
Total cost (US$.$ha^{-1}$)				9.4
E	Machinary/Services	Quantity ($hour^{.}ha^{-1}$)	Unit cost (US$2012.$hour^{-1}$)	Cost (US$2012.$ha^{-1}$)
	Mechanical pasture mowing	0.22	25.60	5.60
Total cost (US$2012.$ha^{-1}$)				5.6

Table S5: Inputs and costs of plantation of corn for silage production

A. Inputs	Quantity ($t.ha^{-1}$)	Unit cost ($US\$2012.t^{-1}$)	Cost ($US\$2012.ha^{-1}$)
Dolomic limestone	3.50	26.94	94.30
Calcium carbonate	2.00	40.96	81.92
Fertilizer, Single Phosphate, N.P.K. 00.18.00	0.30	467.15	140.15
Fertilizer, Potassium chloride, KCl 00.00.60 GR ST S	0.06	830.97	49.86
Micronutrients, FTE BR 12	0.03	345.60	10.37
Fertilizer, N.P.K. 8-30-16 + Zn, 0,5% de Zn	0.30	522.24	156.67
Fertilizer, N.P.K. 25-00-25	0.15	455.68	68.35
Fertilizer, N.P.K. 25-00-25	0.15	455.68	68.35
Desiccant, Nicosulfuron	0.00	12800.00	6.40
Herbicide, Primestra Gold, pre-emergent	0.00	15659.85	62.64
Inseticide, LORSBAN 480 corn	0.00	18254.39	7.30
Physilogycal inseticide, MATCH CE	0.00	51642.69	15.49
Fungicide, OPERA	0.00	72377.19	14.48
Inseticide, Blitz	0.00	3916.80	3.92
Corn seed	0.00	102400.00	102.40
Inseticide, SEMEVIN	0.00	60416.00	12.08
B. Machinary/Services	Quantity ($hour.ha^{-1}$)	Unit cost ($US\$2012.hour^{-1}$)	Cost ($US\$2012.ha^{-1}$)

B.1. Soil management		0.00	0.00
Physical and chemical soil analysis	1.00	15.36	15.36
Mower drag operation, discs: 26 to 28"	2.00	35.84	71.68
Limestone distribution	2.00	40.96	81.92
Heavy harrow disc operation, discs: 32 to 36"	2.00	35.84	71.68
Calcium carbonate distribution	0.50	40.96	20.48
Heavy harrow disc operation, discs: 22"	2.00	25.60	51.20
Fertilizer distribution	1.00	12.29	12.29
Calcium carbonate distribution	0.50	56.32	28.16
Heavy harrow disc operation, discs: 22"	0.80	25.60	20.48
Internal transport	0.25	17.41	4.35

B.2. Corn planting and management	Quantity (hour.ha^{-1})	Unit cost (US$2012.hour^{-1})	Cost (US$2012.ha^{-1})
Corn planting and fertilizer management	0.48	12.29	5.90
Herbicide pulverization		11.78	0.00
Herbicidepulverization, pre-emergent	2.00	11.78	23.55
Inseticide and fungicide pulverization	2.00	12.29	24.58
Desiccant pulverization	1.00	12.29	12.29
Fertilizer distribution	0.30	10.24	3.07
Internal transport	0.50	17.41	8.70

C. Corn harvest for silage production	Quantity (hour.ha^{-1})	Unit cost (US$2012.hour^{-1})	Cost (US$2012.ha^{-1})
Corn harvest	6.25	17.20	107.52
Internal transport	6.25	17.41	108.80

Silage compaction	7.50	10.24	76.80
Silage, lock final procedure	2.00	2.56	5.12
D. Silage removal and distribution	Quantity (hour.ha^{-1})	Unit cost (US$2012.hour^{-1})	Cost (US$2012.ha^{-1})
Silage removal and lading	67.00	2.56	171.52
Silage transport	11.00	10.24	112.64
Silage distribution	11.00	2.56	28.16
E. Silo	Quantity (hour.ha^{-1})	Unit cost (US$2012.hour^{-1})	Cost (US$2012.ha^{-1})
Annual silo costs	1.00	164.30	164.30
Total cost (US$2012.ha^{-1})		0.00	2125.23

Table S6: Inputs and costs of plantation of corn for grain production

A. Inputs	Quantity (t.ha^{-1})	Unit Price (US$2012.t^{-1})	Cost (US$2012.ha^{-1})
Dolomic limestone	3.50	26.94	94.30
Calcium carbonate	2.00	40.96	81.92
Fertilizer, Single Phosphate, N.P.K. 00.18.00	0.30	467.15	140.15
Fertilizer, Potassium chloride, KCl 00.00.60 GR ST S	0.06	830.97	49.86
Micronutrients, FTE BR 12	0.03	345.60	10.37
Fertilizer, N.P.K. 8-30-16 + Zn, 0,5% de Zn	0.30	522.24	156.67
Fertilizer, N.P.K. 25-00-25	0.15	455.68	68.35
Fertilizer, N.P.K. 25-00-25	0.15	455.68	68.35
Desiccant, Nicosulfuron	0.00	12800.00	6.40
Herbicide, Primestra Gold, pre-	0.00	15659.85	62.64

emergent			
Inseticide, LORSBAN 480 corn	0.00	18254.39	7.30
Physilogycal inseticide, MATCH CE	0.00	51642.69	15.49
Fungicide, OPERA	0.00	72377.19	14.48
Inseticide, Blitz	0.00	3916.80	3.92
Corn seed	0.00	102400.00	102.40
Inseticide, SEMEVIN	0.00	60416.00	12.08
B. Machinary/Services			
B.1. Soil management	Quantity (hour.ha^{-1})	Unit Price (US$2012.hour^{-1})	Cost (US$2012.ha^{-1})
Mower drag operation, discs: 26 to 28"	2.00	35.84	71.68
Limestone distribution	1.00	40.96	40.96
Heavy harrow disc operation, discs: 32 to 36"	1.00	35.84	35.84
Calcium carbonate distribution	0.50	40.96	20.48
Heavy harrow disc operation, discs: 22"	2.00	25.60	51.20
Fertilizer distribution	1.00	12.29	12.29
Calcium carbonate distribution	0.50	56.32	28.16
Heavy harrow disc operation, discs: 22"	0.80	25.60	20.48
Internal transport	0.25	17.41	4.35
B.2. Crop Planting	Quantity (hour.ha^{-1})	Unit Price (US$2012.hour^{-1})	Cost (US$2012.ha^{-1})
Corn planting and fertilizer management	0.48	12.29	5.90
Herbicidepulverization, pre-emergent	2.00	11.78	23.55
Inseticide and fungicide pulverization	2.00	12.29	24.58
Desiccant pulverization	1.00	12.29	12.29
Fertilizer distribution	0.30	10.24	3.07
Internal transport	0.50	17.41	8.70

C. Harvest and storage	Quantity (hour.ha^{-1})	Unit Price (US$2012.hour^{-1})	Cost (US$2012.ha^{-1})
Corn harvest	1.00	33.35	33.35
Internal and external transport (from farm to warehouse)	3.49	8.70	30.39
Warehouse cost (allocation, drying and grain cleaning)	58.20	0.87	50.66
Total cost (US$2012.ha^{-1})		0.00	1372.61

Table S7: Inputs and costs of plantation of soybeans production

A. Inputs	Quantity (t.ha^{-1})	Unit cost (US\$2012.t^{-1})	Cost (US\$2012.ha^{-1})
Dolomic limestone	3.50	26.94	94.30
calcium carbonate	2.00	40.96	81.92
Herbicide, Glyphosate	0.00	13633.86	54.54
N.P.K. 0-20-10 c/ micros	0.40	435.20	174.08
Fertilizer, Potassium chloride, KCl 00.00.60 GR ST S	0.10	830.97	83.10
Micronutrients, FTE BR 12	0.06	345.60	20.74
Fungicide, seeds treatment, Vitavax Thiram	0.00	10240.00	5.12
Inseticide, Standak	0.00	196231.17	3.92
Microbial inoculant	0.00	1792.00	3.58
Herbicide, Trifuralina, Milenia	0.00	16687.89	33.38
Inseticide, Dimilin	0.00	47816.87	1.43
Inseticide, LORSBAN 480	0.00	18254.39	4.56
Inseticide, Nomolt	0.00	40960.00	2.05
Inseticide, Acefato	0.00	18513.67	5.55
Inseticide, Engeo Pleno	0.00	69405.57	13.88
Inseticide, Thiodam EC	0.00	14516.53	3.63
Fungicide, Opera	0.00	72377.19	72.38
Fungicide, Priori Xtra	0.00	74898.58	22.47
Fungicide, Derozal Plus	0.00	23738.45	11.87
Mineral oil, Assist	0.01	2560.00	23.04
Trangenic soybean seed, Syngenta 9070 or Potencia	0.07	1152.00	74.88
B. Machinary/Services			
B.1. Soil management	Quantity (hour.ha^{-1})	Unit cost (US\$2012.hour^{-1})	Cost (US\$2012.ha^{-1})
Mower drag operation, discs: 26 to	2.00	35.84	71.68

28"			
Limestone distribution	1.00	40.96	40.96
Heavy harrow disc operation, discs: 32 to 36"	1.00	35.84	35.84
Calcium carbonate distribution	0.50	40.96	20.48
Heavy harrow disc operation, discs: 22"	2.00	25.60	51.20
Fertilization operation	1.00	12.29	12.29
Soil terrace operation	0.50	56.32	28.16
Fertilization and seed planting	0.48	12.29	5.90
Desiccant pulverization	1.00	12.29	12.29
Herbicide operation	1.00	11.78	11.78
Herbicide operation	1.00	11.78	11.78
Inseticide and fungicide operation	9.00	12.29	110.59
Crop fertilization	1.00	10.24	10.24
C. Harvest and storage	Quantity (hour.ha^{-1})	Unit cost (US$2012.hour^{-1})	Cost (US$2012.ha^{-1})
Harvest, grains, machine costs	1.00	33.35	33.35
Transportation (from farm to warehouse)	2.04	8.70	17.73
Warehouse cost (allocation, drying and grain cleaning)	33.95	0.87	29.55
Total cost (US$2012.ha^{-1})			1294.22

Table S8: Farm annual maintenance costs[1]

Variable	Price (US$2012.ha^{-1}.yr^{-1})
Working animals, horse	
Depreciation	0.08
Interest	0.03

Machinery and equipment	0.00
Depreciation	6.91
Interest	2.34
Veterinary equipements	0.00
Depreciation	0.11
Telephone device	0.00
Depreciation	0.03
Farmer minimum living expenses	0.49
Maintenance of machinery and equipment	5.70
Services and labor	6.63
Fuel and lubricant	2.06
Taxes and fees	0.62
Total farm costs	24.99

[1] Costs as proposed by Costa et al. (2005) cost structure.

Table S9: List of LCA values according to inputs application and machinery operations.

Inputs	LCA factor (kg of CO_2-e.(kg of input)$^{-1}$)
Calcium carbonate	2.12E-03
Corn seed	1.93E+00
Dolomitic limestone	2.12E-03
Fertilizer, N.P.K. 25-00-25 (substituted by urea)	3.30E+00
Fertilizer, N.P.K. 8-30-16 + Zn, 0,5% de Zn (substituted by SSP)	2.62E+00
Fertilizer, Potassium chloride, KCl 00.00.60 GR ST S	4.97E-01
Fertilizer, Single Phosphate, N.P.K. 00.18.00	2.62E+00
Fungicide, Derozal Plus	1.06E+01
Fungicide, Opera	1.06E+01
Fungicide, Priori Xtra	1.06E+01
Herbicide, Primestra Gold, pre-emergent	1.02E+01
Herbicide, Trifuralina, Milenia	1.02E+01
Insecticide, Dimilin	1.66E+01
Insecticide, Nomolt	1.66E+01
Insecticide, Standak	1.66E+01
Insecticide, Thiodam EC	1.66E+01
Insecticide, Acefato	1.66E+01
Insecticide, Blitz	1.66E+01
Insecticide, Engeo Pleno	1.66E+01
Insecticide, LORSBAN 480	1.66E+01
Insecticide, SEMEVIN	1.66E+01
Microbial inoculant	NA[1]
Micronutrients, FTE BR 12	NA
Physilogycal Insecticide, MATCH CE	16.6
Seeds (Brachiaria brizantha cv. Marandu)	1.90E+00
Transgenic soybean seed, Syngenta 9070 or Potencia	9.60E-01
Urea	1.52E+00

Machinery operations with area-proportional LCA	LCA factor (kg of CO_2-e.(ha of service)$^{-1}$)
Calcium carbonate distribution	2.53E+01
Corn harvest for silage	3.25E+02
Desiccant pulverization	1.10E+01
Desiccant, Nicosulfuron	1.02E+01
Fertilization and pasture planting	2.27E+01
Fertilization and seed planting	9.83E+01
Harvest, grains, machine costs	3.25E+02
Heavy harrow disc operation, discs: 22"	2.47E+01
Heavy harrow disc operation, discs: 32 to 36"	6.23E+01
Herbicide pulverization (ppi or "pre")	1.10E+01
Insecticide and fungicide pulverization	1.10E+01
Limestone distribution	2.53E+01
Mechanical pasture mowing	2.33E+01
Mineral oil, Assist	1.73E+00
Mower drag operation, discs: 26 to 28"	2.47E+01
Silage compaction	NA
Silage, lock final procedure	NA
Soil terrace	1.18E+02
Urea distribution	2.53E+01
Machinery operations with weight and distance-proportional LCA[2]	**LCA factor kg of CO2-e.(tkm of service)$^{-1}$**
Internal transport	4.84E-01
Silage transport and distribution	4.84E-01
Machinery operations with volume-proportional LCA	**LCA factor (kg of CO2-e.(m^3 of service)$^{-1}$)**
Silage removal and lading	6.24E-01

[1] Not available

[2] tkm = tonnes times kilometres

Table S10: Pasture area scenarios and associated deforestation.

Baseline projection (A_{BAU}) and altered projections, $A_{BAU-30\%}$ and $A_{BAU+30\%}$, generated as a function of the demand scenarios $D_{BAU-30\%}$ and $D_{BAU+30\%}$, assuming that every 1% variation in demand causes a variation of 0.4% in pasture area (k = 0.4).

	Total area (M ha)			Deforested area* (M ha)		
Year	A_{BAU}	$A_{BAU-30\%}$	$A_{BAU+30\%}$	A_{BAU}	$A_{BAU-30\%}$	$A_{BAU+30\%}$
2015	68.9	65.8	72.0	0.0	0.0	2.5
2020	69.2	64.4	74.1	0.4	0.0	5.0
2025	69.8	63.1	76.4	0.9	0.0	7.9
2030	70.4	62.0	78.8	1.5	0.0	10.9

* Accumulated from 2006

Table S11:Protein content, relative equivalence with beef and carbon footprint for Brazilian broiler meat.

Meat	Protein content[1]	Beef Equivalence protein	C footprint[2] (kg CO_2-e/kg of product)
Beef	0.17	1.00	-
Broiler	0.19	0.89	5.84

[1] http://www.fao.org/ag/ags/post-harvest-management/meat-meat-products/background-and-meat-consumption/composition-of-meat/en/

[2](MacLeod et al., 2013). Note for part of the analysis unpublished Brazil-specific emission factors from the same study were used.

Supplementary Figures

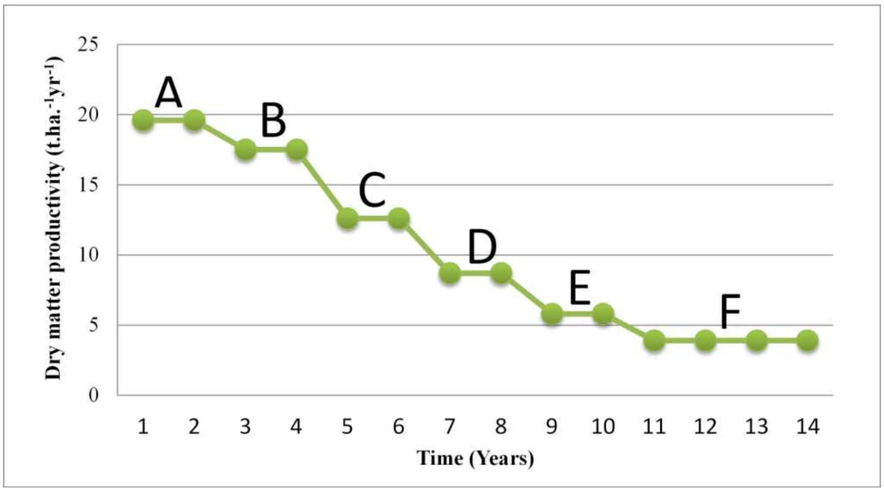

Figure S1: Discrete representation of pasture degradation of Brachiaria Brizantha.

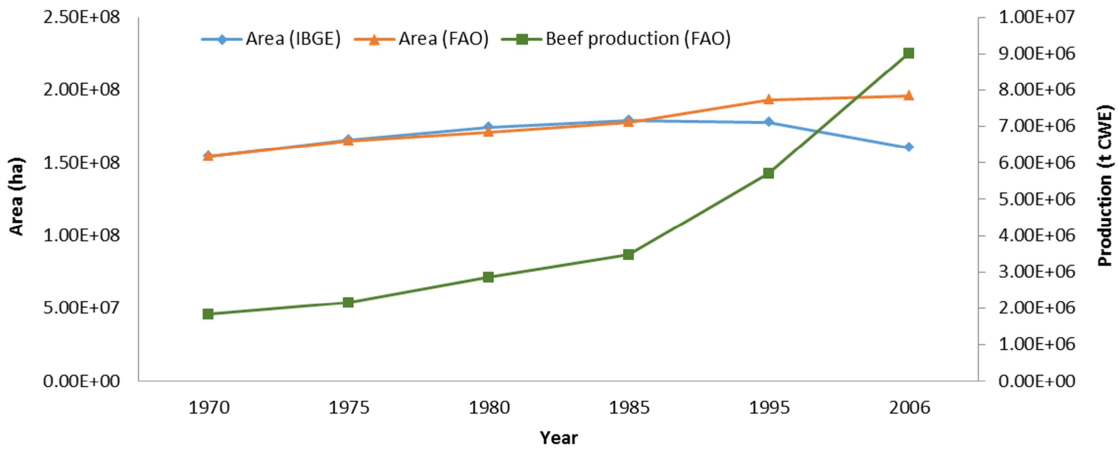

Figure S2:Comparison between beef production and pasture area using Brazilian agricultural Census (IBGE) and FAO estimates. * 2006 is the last agricultural census.

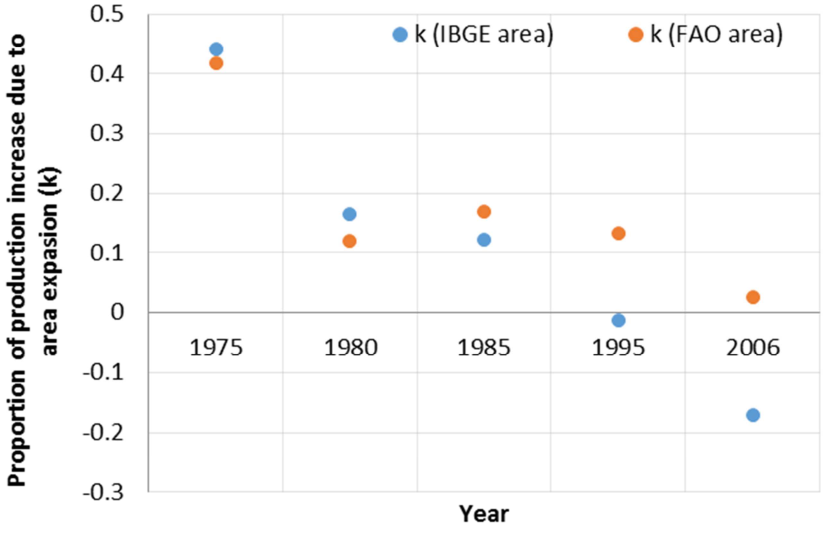

Figure S3:calibrated values for k.

Appendix 2: paper 1

De Oliveira Silva, R., Barioni, L.G., Albertini, T.Z., Eory, V., Topp, C.F.E., Fernandes, F.A., Moran, D., 2015. Developing a nationally appropriate mitigation measure from the greenhouse gas GHG abatement potential from livestock production in the Brazilian Cerrado. Agric. Syst. 140, 48–55. doi:10.1016/j.agsy.2015.08.011

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Developing a nationally appropriate mitigation measure from the greenhouse gas GHG abatement potential from livestock production in the Brazilian *Cerrado*

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Linear programming

ABSTRACT

Brazil is one of the first major developing countries to commit to a national greenhouse gas (GHG) emissions target that requires a reduction of between 36.1% and 38.9% relative to baseline emissions by 2020. The country intends to submit agricultural emissions reductions as part of this target, with livestock production identified as offering significant abatement potential. Focusing on the *Cerrado* core (central Brazilian savannah), this paper investigates the cost-effectiveness of this potential, which involves some consideration of both the private and social costs and benefits (e.g. including avoided deforestation) arising from specific mitigation measures that may form part of Brazil's definition of Nationally Appropriate Mitigation Measures (NAMAs). The analysis used an optimisation model to define abatement costs. A baseline projection suggests that beef production in the region will emit 2.6 Gt CO_2e (CO_2 equivalent) from 2010 to 2030, corresponding to 9% of national emissions (including energy, transport, waste, livestock and agriculture). By implementing negative-cost measures identified in a marginal abatement cost curve (MACC) by 2030, the 2.6 Gt CO_2e could be reduced by around 24%. Pasture restoration, involving avoided deforestation, offers the largest contribution to these results. As the Brazilian *Cerrado* is seen as a model for transforming other global savannahs, the results offer a significant contribution by identifying alternatives for increasing productivity while minimizing national and global external costs.

1. Introduction

Global demand for livestock products is projected to grow by 70% by 2050 (Gerber et al., 2013). This is expected to generate significant additional pressure on producers and on natural resources. Sustainable management (or intensification) will require increasing yields and efficiency in existing ruminant production systems, minimizing competition of land used for food and feed, while maximizing ecosystem services, including mitigation of greenhouse gas (GHG) emissions (Gerber et al., 2013; Soussana et al., 2013; Thornton and Herrero, 2010).

Tropical regions are implicated as potentially offering major opportunities to increase beef productivity and emissions mitigation, as current productivity levels are still relatively low and emission intensities correspondingly high (Opio et al., 2013; Gerber et al., 2013).

More productive pastures can increase soil carbon stocks, providing one of the largest terrestrial carbon sinks (Follett and Reed, 2010; Neely et al., 2009), in a pool that is a more stable form than the aerial components of forests (Soussana et al., 2010). But potential carbon sequestration in soils under grasslands far from offsets the loss of above ground vegetation in the majority of tropical areas, and therefore natural vegetation should be preserved.

Brazil is the world's second largest beef producer — 9.3 Mt yr^{-1} (14.7% of the world's total), and the largest exporter in 2012–13 (FAO, 2014). Production is predominantly pasture-based in a grassland area of approximately 170 Mha (IBGE, 2014), mostly in a humid or sub-humid tropical climate.

But beef production can entail significant trade-offs, that must be managed to minimize external costs. These include the controlled expansion of agricultural area, associated deforestation, cost-effective greenhouse gas mitigation, and land competition between food and biofuels.

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Analysis of historical data (Martha et al., 2012) and scenario studies conducted by the World Bank (de Gouvello et al., 2011) suggest that improving beef productivity has the highest potential to buffer the expansion of other agricultural activities, avoiding further deforestation. Increasing pasture productivity can also boost soil carbon sequestration, particularly when carried out in currently degraded grasslands (Braz et al., 2013; Ruviaro et al., 2014). In addition, increasing productivity through feed supplementation may significantly reduce direct methane emissions (Berndt and Tomkins, 2013; Ruviaro et al., 2014).

In this context and based on its previous National Plan on Climate Change, at the Conference of the Parties 15 (COP 15), Brazil has proposed Nationally Appropriate Mitigation Actions (NAMAs) as part of its commitment to the United Nations Framework Convention on Climate Change (http://www.mmechanisms.org/e/namainfo/index.html). Over the period 2010–2020, the NAMAs establish targets for the reduction of Amazon deforestation by 80% and by 40% in the *Cerrado* (Brazilian savannah), through the adoption of pasture recovery (15 Mha), and from integrated crop–livestock–forestry systems (4 Mha). With these cattle-related measures, Brazil expects to reduce net emissions by between 101 and 126 Mt CO_2e, by 2020, which account for 61–73% of all mitigation in agricultural practises by the NAMA route. The NAMA proposal is enacted as part of the ambitious ABC (Agricultura de Baixo Carbono — Low Carbon Agriculture) programme, which offers low interest credit lines to farmers adopting mitigation technologies (Mozzer, 2011).

This paper investigates the cost-effectiveness of key livestock mitigation measures applicable in the *Cerrado* core (central Brazilian savannah); a region that contains around 35% of the Brazilian herd (Anualpec, 2010). The region is considered as central in Brazil's ascendance in global production (The Economist, 2010; The New York Times, 2007) and is still regarded as the most important region for expanding beef production in Brazil (Ferraz and Felício, 2010). It is seen as a potential model for transforming other savannahs (Morris et al., 2012).

The analytical focus is significant because there is currently little research clearly demonstrating that mitigation through livestock management can be delivered at relatively low cost. The paper offers the first bottom-up cost-effectiveness analysis using an optimisation model for Brazilian beef production. The measures evaluated are pasture restoration, feedlot finishing, supplement concentrates and protein and nitrification inhibitors. The analysis uses the outputs of a multi-period linear programming model to develop a bottom-up or engineering marginal abatement cost curve (MACC), to represent the relative cost-effectiveness of measures and their cumulative abatement potential above a baseline of business as usual (Moran et al., 2010). The analysis examines the direct emissions reductions attributable to measures enacted within the notional farm gate rather than wider life cycle impacts (i.e., post farm gate), and accounts for both the private and social costs and benefits (e.g. including avoided deforestation).

The paper offers new insights for regional policy and is structured as follows. Section 2 outlines the modelling structure and relevant optimisation assumptions underlying the cost-effectiveness analysis. Section 3 describes the MACC calculation, while Section 4 sets out results. Sections 5 and 6 offer a discussion and conclusions.

2. Modelling methods for mitigation cost-effectiveness

2.1. Model overview

Abatement potential and cost-effectiveness of measures were derived using a multi-period linear programming model (see Appendix: Supplementary material for detailed mathematical description) that simulates a whole cycle (cow–calf, stocking and finishing) beef production farm, accounting for: (i) herd dynamics, (ii) financial resources, (iii) feed budgeting, (iv) land use: pasture recovery dynamics and crops, and (v) soil carbon stock dynamics.

The model optimises the use of the farm resources (capital, cattle, land) while meeting demand projections and maximizing profit. In this context the model is used to simulate beef production treating the *Cerrado* region as a single farm. The farm activities (i–iii) are modelled using monthly time steps, while (iv & v) are modelled using annual time steps. The model represents animals in age cohorts k; a steer of age cohort $k = 1$, is a calf aged 6 months, and 189 kg of live weight (LW). After 3 months in the system, age cohort k is transferred to age cohort $k + 1$, now with 222 kg of LW. The final weight is 454 kg, corresponding to $k = 9$ (33 months), when the animal is sold and removed from the system.

The same cohorts apply to heifers, although these can also accommodate breeding rates, where a heifer generates 1 calf per 18 month cycle, comprising 9 months of pregnancy, 6 months of lactation (Millen et al., 2011), plus 3 months of non-lactation and non-pregnancy. Half of the calves born are allocated to steers and the other half are allocated to heifers, both of age cohort $k = 1$. After 4 cycles, the cows are removed from the system and slaughtered, i.e., used to meet demand.

The model also simulates feedlot finishing, and thus allows the reduction of the finishing time. It can remove a proportion of steers from exclusive grazing, inserting the animals into feedlot systems; generally only males are confined in Brazil (Millen et al., 2009; Costa Junior et al., 2013). For all cattle categories, i.e., male, female, male in feedlot and breeding females, the corresponding age cohort is associated with specific parameters: weight, mortality rate, dry matter (DM) intake, selling and purchase prices, emissions factors for CH_4 from enteric fermentation and emissions factors for N_2O from excreta. The associated coefficient values are detailed in Tables S1 and S2 (Appendix: Supplementary tables).

The gross margin of the *Cerrado* single region farm is maximized and calculated as the difference between the income and expenses. Income derives exclusively from the sale of finished cattle, 454 kg of LW for steers and 372 kg of LW for heifers. Farm expenses are composed of investment and maintenance costs. Maintenance costs are (i) farm maintenance and (ii) animal non-feed maintenance. Costs for (i) include working animals, machinery and equipment, veterinary equipment, telephone device, fuel, taxes and fees, totalling US\$ 25.00 $ha^{-1}yr^{-1}$ (see Appendix: Supplementary Table S8 for details). Costs for (ii) were calculated for each age cohort and it is composed of cost of mineral salt and expenses with health (vaccines), and animal identification (Appendix: Supplementary Table S1).

2.2. Land use dynamics

The model simulates land use dynamics by allocating the total area across pastures or crops; the latter being used for grain and silage production to be used for the formulation of ration for feedlot and supplementation for grazing cattle. The model allocates land into pasture, soybean and corn. In the case of pasture, the model allocates land into different productivity levels. Pasture degradation and restoration rates are key model processes that have a bearing on overall system productivity and hence emissions intensity of production.

2.2.1. Grassland degradation

Pasture degradation can be defined as the loss of vigour and productivity of forage. To represent the degradation process, we define six levels of dry matter productivity (DMP): *A*, *B*, *C*, *D*, *E* and *F* (Table 1), where level *A* is the pasture of highest productivity, and level *F* is fully degraded. If no action is taken to maintain or improve productivity of a fraction of the area in a given level, it is relocated to a lower productivity level. So, after a period of time (assumed as two years herein) level *A* degrades to level *B*, *B* degrades to *C*, and so on, until pasture *F*, thus completing a 10 years full degradation (with no management interventions).

Table 1
Annual dry matter productivity and equilibrium C stock values in function of land use.

Land use	DM[a] ($t\ ha^{-1}\ yr^{-1}$)	Soil carbon stock equilibrium[b] ($t\ ha^{-1}$)
Pasture *A*	19.6	84.3
Pasture *B*	17.6	82.7
Pasture *C*	12.6	62.3
Pasture *D*	8.7	45.2
Pasture *E*	5.8	32.4
Pasture *F*	3.9	26.1
Corn (silage)	9.0	45.0
Corn (grain)	3.8	40.0
Soybean	2.5	45.0

[a] Estimated using the model published by Tonato et al. (2010).
[b] According to Parton et al. (1987).

The DMP of the pastures levels were calculated exogenously using a model that estimates seasonal pasture growth according to soil, species and climate conditions (Tonato et al., 2010). Each pasture level of DMP is associated with a carbon equilibrium value that is used to estimate changes in soil organic carbon due to pasture management (see Section 2.3 for details).

2.2.2. Land use change and pasture restoration

To offset the degradation process the model can allow for grassland restoration through improved forage quality by direct restoration (by chemical and mechanical treatment) or indirect restoration (by rotating with crops). For example, in a given year a pasture *A* will degrade to *B*, the optimal solution might be letting half of pasture *A* to degrade, and half be maintained to level *A*. Furthermore, the model works simultaneously with a composition of pasture DMP levels; e.g., in a given year *t*, the composition can be 4% of *A*, 10% of *B*, 85% of *C*, and 1% of soybean. Then, at year $t + 1$, the composition can change by any combination among the pasture DMP levels and crops.

For each type of land use change or restoration, there is an associated cost (Table 2). Costs were calculated accounting for the amount of inputs and farm operations (e.g., nitrogen, limestone, micronutrients, forage seeds, internal transport) needed to maintain or increase the DMP level in the target pasture DMP level. For details of applied inputs, see Tables S3–S7 in Appendix: Supplementary tables.

Land use change (including deforestation), degrading or restoring pasture will affect the soil carbon (C) stocks. These changes are calculated by estimating the annual C stock under pasture and crops for each land use. The total accumulated C under soils is given by the sum of the C stock of each pasture DMP levels, soybean and corn.

2.3. Carbon sequestration through pasture management

Depending on the DMP, the C flux may change significantly. The model works with equilibrium values of the C stock for each type of pasture and crops. The higher the pasture productivity, the higher the C equilibrium value (Table 1). The equilibrium values were calculated exogenously, using simulations from the CENTURY model (Parton et al., 1987) applied to *Cerrado* biophysical characteristics and using the annual DMP calculated for each pasture category.

The model accounts for the annual carbon stocks per each land use in column 1, Table 1. The model transfers the accumulated carbon from year $t-1$ to year t and calculates the variation of soil C in year t.

Letting $C_{t,lu}$ be the soil carbon stock (tonnes) under the land use lu, where $lu \in \{A, B, C, D, E, F, \text{soybean}, \text{corn (silage)}, \text{corn (grain)}\}$. Then $C_{t,lu}$ can be expressed by:

$$C_{t,lu} = \varphi(t, lu) + \Delta C_{t,lu} \tag{1}$$

and

$$\Delta C_{t,lu} = f(\varepsilon_{lu}, C_{t-1,lu}). \tag{2}$$

Eq. (1) is composed of the carbon transference term, $\varphi(t,lu)$, and the C sequestration term, $\Delta C_{t,lu}$. The term $\varphi(t,lu)$ accounts the transference of C from other uses to land use lu in year t; e.g., if lu is equal pasture *B*, and one hectare of soybean is converted in year t into one hectare of pasture level *B*, the carbon previously stocked under soybean has to be transferred to pasture *B*. Similarly, if some hectares are converted from pasture *B* to pasture *A*, or degraded to *C*, then part of the C stock from *B* has to be proportionally transferred from *B* to these other uses. The sequestration term, $\Delta C_{t,lu}$ is written as a function of the difference between the previous C stock $C_{t-1,lu}$, and the C stock equilibrium value, ε_{lu}. Hence the further the previous stock is from the equilibrium value, the more C will be up taken. Conversely, if due to the land use change, or degradation, the C stock becomes greater than the equilibrium value, there will be negative C sequestration, i.e., a loss of C stock. These modelling approaches follow the concepts suggested by Eggleston et al. (2006) and Vuichard et al. (2007). The extended version of Eqs. (1) and (2) are presented in Appendix: Supplementary material.

2.4. Deforestation due to cattle ranching

For pasture area we use the projections published by de Gouvello et al. (2011) combined with an endogenous deforestation term. Let LU_t be the total area at year t; a_t the exogenous projections; and D_t the endogenous term that represents further area expansion. Then for every year:

$$LU_t = a_t + D_t. \tag{3}$$

The deforested area will cause a loss of carbon stocks in natural vegetation and influence soil C; and directly influences the transference term in Eq. (1), i.e., loss of soil organic matter (SOM). Both vegetation

Table 2
Costs of pasture restoration practises and crops planting. The table can be read as "the cost to restore one hectare of pasture '*X*' to an improved pasture '*Y*'", or in some cases, "the cost to move one hectare from land use '*X*' to land use '*Y*'", where "*X*" and "*Y*" are any element in the column "Pasture/crop". The case of $X = Y$ (table diagonal), represents the cost of maintaining a given pasture at the current DMP level (i.e., cost of avoiding degradation) or the cost of replant a crop in the same area.

Land use	Costs of pasture restoration practises/land use change[a] (US$ 2012 ha^{-1})								
	Pasture *A*	Pasture *B*	Pasture *C*	Pasture *D*	Pasture *E*	Pasture *F*	Corn (silage)	Corn (grain)	Soybean
Pasture *A*	112.4	0.0	0.0	0.0	0.0	0.0	1352.6	600.0	345.4
Pasture *B*	149.9	72.7	0.0	0.0	0.0	0.0	1502.5	749.9	495.3
Pasture *C*	399.3	249.4	15.0	0.0	0.0	0.0	1751.9	999.3	744.7
Pasture *D*	630.0	480.0	230.7	9.4	0.0	0.0	1982.6	1229.9	975.3
Pasture *E*	724.6	574.6	325.2	94.6	5.6	0.0	2077.2	1324.5	1069.9
Pasture *F*	767.0	617.1	367.7	137.1	42.5	5.6	2119.6	1367.0	1112.4
Corn (silage)	269.8	200.9	125.1	125.1	125.1	125.1	1630.7	1060.6	971.8
Corn (grain)	269.8	200.9	125.1	125.1	125.1	125.1	1736.4	981.9	992.6
Soybean	269.8	200.9	125.1	125.1	125.1	125.1	1736.4	981.9	1017.7

[a] See Appendix: Supplementary material for calculation details.

carbon stocks and SOM are accounted to represent the emissions associated with deforestation.

There is limited quantitative research accounting for the dynamics of pasture productivity following deforestation. In accordance with the best available information, the model allocates new converted areas into the system in pasture category *C* (the highest without nitrogen fertilization), as soil carbon also can increase or decrease values after deforestation (Maia et al., 2009) and pasture productivity is relatively high after conversion due to higher soil organic matter mineralization (Martha et al., 2007). In this analysis, we assumed the cost of opening new areas is zero because the cost of conversion the *Cerrado* into pastures can be offset by timber sales and land value appreciation (Bowman et al., 2012).

Another assumption is that the model cannot discard land endogenously, neither does it allow fallow in any year of the planning period. This assumption is based on the fact that cattle ranchers are not allowed to let their properties be unproductive; otherwise the land can be confiscated by the government for agrarian reform (Federal Law 8.629 — www.planalto.gov.br/ccivil_03/leis/l8629.htm).

2.5. Baseline construction

Land use change scenarios need to be mapped onto a plausible baseline for land use activity. The baseline scenario is based on national forecasts of beef demand and grassland area for Brazil, from 2006 to 2030 (de Gouvello et al., 2011). The assumption is that the attributable *Cerrado* pasture area and beef demand share are a fixed proportion of the national projections. In 2006, the *Cerrado* pasture area represented 34% of the national total (IBGE, 2014). The model then assumes that *Cerrado* pasture area corresponds to 34% of Brazil's pasture area, and this proportion is constant during the studied period (2006–2030). Similarly, as there is no data for regional demand, we assumed demand to be proportional to area, i.e., demand for *Cerrado* is also equivalent to 34% of national demand, this percentage is very close to the 35% figure estimated by Anualpec (2010).

In the model, increased productivity occurs by means of investments in technologies, e.g., pasture restoration, supplementation and feedlot animals. The baseline scenario has limited adoption of these measures, implying constant productivity. We assumed that pasture restoration is allowed in the baseline only to avoid degradation, but it is constrained to maintain productivity at 2006 levels (10 t DM ha^{-1} yr^{-1}, as calculated in Appendix: Supplementary material). Combining this constraint with projected increased demand pushes the model to open new areas if it is necessary to meet the growing demand for beef.

The current adoption rate of feedlot finishing in Brazil is around 10% of the total herd (Anualpec, 2010). We assumed this proportion to be constant in the baseline, a rate that is in counterpoint to a higher level of penetration of this measure in a mitigation counterfactual.

2.6. GHG emissions sources

The model calculates GHG emissions using emissions factors for activities within the farm gate. GHG emissions associated with the 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 direct emissions from N fertilization; (d) CO_2 from deforestation; and (e) CO_2 from pasture degradation and land use change from pasture to crops. Items (a) and (b) depend on herd composition: each age cohort of males and females (heifer or cow) has an associated emission factor of CH_4 and N_2O calculated using Tier 2 methodology (Eggleston et al., 2006), see Table S1 and Table S2 (Appendix: Supplementary tables). Due to the lack of studies in Brazilian conditions, for (c), we used the Tier 1 IPCC default factor of 1% (Eggleston et al., 2006). The emissions from (d) are calculated using coefficient of loss of natural vegetation per deforested area. The average carbon loss of natural vegetation due to deforestation was estimated as 34.6 tonnes of C per hectare, in accordance to Eggleston et al. (2006) and Bustamante et al. (2012). For (e), the emissions are calculated according to Eqs. (1) and (2).

2.7. Mitigation measures

The selection of GHG mitigation measures was based on literature review and expert opinion regarding the relevance and applicability of the technologies to Brazilian livestock production and conditions. The measures evaluated are: concentrate supplementation, protein supplementation, pasture restoration, nitrification inhibitors and feedlot finishing. Although the latter is already in the baseline, we investigated a higher adoption rate of this technology.

Modelling assumptions for these measures related to the effects the measures have upon the gross margin and emissions are detailed in Table 3.

2.7.1. Concentrate and protein supplementation

Both measures involve supplementing the feed of grazing steers; e.g., feed is composed of forage and supplements. It is expected that these measures reduce emissions since animals gain weight faster and take less time to be finished.

Biological coefficients, e.g., mortality rate, weight, DM intake, and emissions factor for steers fed with supplementations can be found in Table S2 in Appendix: Supplementary tables.

2.7.2. Pasture restoration

This measure works in the model by avoiding deforestation and because restoration boosts carbon soil uptake. Details of the modelling and costs are explained in Section 2.2.2. In contrast to the baseline scenario, to evaluate this measure, the fixed DMP baseline constraint was removed.

2.7.3. Nitrification inhibitors

The measure works by avoiding a proportion of the N in fertilizer or manure being converted into N_2O, i.e. nitrification and denitrification process (Abbasi and Adams, 2000). To date there have been no studies detailing the reduction in N_2O emissions for Brazilian pastures when nitrogen inhibitors are applied. A 50% reduction of direct N_2O emissions is assumed in this paper — as found by Giltrap et al. (2011) for a New Zealand study. We assumed that this measure is applicable only over the N used for pasture and crops fertilization. The reason is that most of the Brazilian herd is based on a grazing system where it is unfeasible to apply inhibitors to animal excreta.

2.7.4. Feedlot finishing

Like supplementation, this measure works by reducing the cattle finishing time since feedlot animals are fed only by ration (with the formulation described in Table 4). Only steers can be selected to model in the feedlot system. The adoption rate was arbitrarily assumed to be 15% of the total finished herd, since in the baseline the adoption rate is 10% of the total finished herd, the measure can be stated as: increasing by 50% over the baseline adoption rate.

3. Marginal abatement cost curve

A MACC can be used to represent the relative cost-effectiveness of different abatement options and the total amount of GHG that can be abated by applying mitigation measures over and above a baseline scenario. The aim is to identify the most economically efficient manner to achieve emissions reduction targets, where the cheapest units of greenhouse gas should be abated first (Moran et al., 2010).

MACC analysis can be derived by means of a top-down analysis — which usually makes use of a general equilibrium model and emissions are calculated endogenously, or by a bottom-up or engineering analysis (MacLeod et al., 2010). This paper takes a bottom-up approach, where the individual abatement potential of measures and their costs are individually modelled.

Table 3
Selected livestock mitigation measures.

Mitigation measure	Description	Cost[a]	Unit	Reduces emissions by:	Adoption rate target
Feedlot finishing	When cattle weight is around 80% of the slaughter weight it is removed from pasture and grass to feedlot on a diet with ration of balanced protein and energy content	9.12	$ $head^{-1}$ $month^{-1}$	Shorter animal life cycle by increasing weight gain	15% of the total finished animals
Nitrification inhibitors	Application of Agrotain Plus® together with urea used as fertilizer; 3 g per kg of applied nitrogen[b]	61.44	$ t^{-1}	Reduced conversion of nitrogen to the GHG nitrous oxide (nitrification)	Optimised
Pasture restoration	Improving pasture forage productivity by soil chemical and mechanical treatment. As described in Section 2.2.2	Table 2	$ ha^{-1}	Avoiding the need for additional pasture land and increasing organic carbon sequestration	Optimised
Supplementation concentrate	Feeding cattle via grazing and a ration with a high energy content. Grazing steers with 421 kg of LW can be selected for concentrate supplementation. The supplementation takes 2 months and the final weight is 490 kg	3.07	$ $head^{-1}$ $month^{-1}$	Shorter animal life cycle by increasing weight gain	Optimised
Supplementation protein	Feeding cattle via grazing and a ration with a high protein content. Calves (189 kg) can be selected (only in March) to be supplemented with protein. The steers are finished after 15 months, with 481 kg	1.15	$ $head^{-1}$ $month^{-1}$	Shorter animal life cycle by increasing weight gain	Optimised

[a] In the case of supplementations the values refer to non-feed costs, for feed costs see ration formulation (Table 4).
[b] According to manufacturer's recommendation (http://www.agrotain.com/us/home).

Table 4
Rations (supplements) formulation and costs.

Crop	Ration formulation (%)[a]			Cost[b] (US$ kg^{-1})
	Feedlot	Concentrate	Protein	
Corn (grain)	83	80	15	PBF
Corn (silage)	11	0	0	PBF
Soybean	5	17	39	PBF
Urea	0	2	12	1.19
Mineral salt	1	1	19	0.84
NaCl	0	0	15	1.19

[a] Rations were formulated by using the software Invernada (minimum cost ration formulator) (Barioni, 2011).
[b] PBF = produced by the farm, i.e., corn and soybean are not purchased but produced endogenously in the model.

The MACC can be presented in form of a histogram, where the C abatement potential lies on the x-axis, and the cost per tonnes of abatement in the y-axis. The abatement potential of a measure m (AP_m) is calculated as the annual average of the difference between the business-as-usual (baseline) total GHG emissions (E_{BAU}) and the total emissions under the mitigation measure scenario (E_m) during the production period T:

$$AP_m = \frac{E_{BAU} - E_m}{T}. \quad (4)$$

The cost-effectiveness of measure m (CE_m), therefore, is calculated by:

$$CE_m = \frac{GM_{BAU} - GM_m}{AP_m} \quad (5)$$

where GM_{BAU} and GM_m are, respectively, the gross margin in the baseline scenario and the gross margin in the scenario with the measure m implemented.

As observed in Eqs. (4) and (5), AP_m and CE_m are average values across the planning period.

4. Results

4.1. Baseline emissions

In the baseline scenario, beef production in the *Cerrado* accounts for an average of 121.5 Mt CO_2e yr^{-1}, from 2010 to 2030. This value includes enteric fermentation, animal waste (emissions from excreta), soil fertilization emissions, pasture (due to the loss in C stocks), and deforestation driven by cattle production (Fig. 1). The accumulated emissions from 2010 to 2020 account for about 1249 Mt CO_2e or 2551 Mt CO_2e from 2010 to 2030.

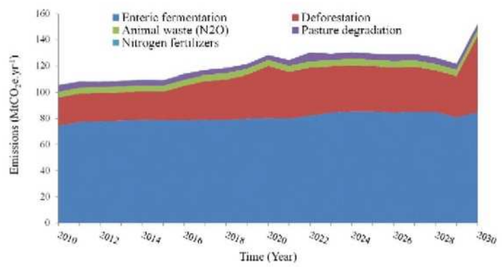

Fig. 1. Baseline emissions of beef production in the Brazilian *Cerrado* for the 2010–2030 period according to: nitrogen fertilizer (applied to pastures restoration and crops plantation), animal waste (cattle direct N_2O emissions through excreta), pasture degradation (loss of soil organic carbon) and deforestation (loss of above ground organic carbon).

R. de Oliveira Silva et al. / Agricultural Systems 140 (2015) 48–55

In relative terms, enteric fermentation makes the biggest contribution to the total: 66% of emissions, followed by deforestation, with 26%. The results also show that pasture degradation is a considerable source of emissions, accounting for an average of 8.35 Mt CO_2e yr^{-1} (an average of 0.06 t CO_2e ha^{-1} yr^{-1}), the equivalent to 4% of emissions or the same proportion as animal waste (Fig. 2).

de Gouvello et al. (2011) suggests that total national GHG emissions from energy, transport, waste, livestock and agriculture, will be around 1.70 Gt CO_2e by 2030. The results presented here suggest that beef production in the *Cerrado* will be responsible for about 152 Mt CO_2e in 2030, corresponding to 9% of total national GHG emissions.

In the baseline scenario, without increasing productivity, an average deforestation rate of 246.1×10^3 ha yr^{-1} would be required to meet the beef demand projections.

Emissions attributed to the use of fertilizers were not significant, accounting for an average of 0.2 Mt CO_2e yr^{-1}. This was expected, since small amounts of N are used to fertilize *Cerrado* pasture soils (Martha et al., 2007; Cederberg et al., 2009).

4.2. Cost-effectiveness analysis

For policy purposes it is important to detail the relative cost of emissions mitigation measures. Three of the five mitigation measures simulated — concentrate supplementation, protein supplementation, and pasture restoration — have negative cost-effectiveness: US$ −8.01 t CO_2e^{-1}, US$ −2.88 t CO_2e^{-1} and US$ −0.05 t CO_2e^{-1}, respectively (Fig. 3). Adopting these measures implies cost savings while reducing emissions. These measures work by balancing the loss of DM production during the dry months. The *Cerrado* biome is predominantly seasonal tropical, meaning dry winters and rainy summers, with lower pasture productivity during the dry months. If cattle are supplemented with concentrates or protein they can be finished earlier, thereby reducing emissions.

Due to the large applicable area (approximately 60 Mha), and given the current low productivity of 10 t DM ha^{-1} yr^{-1}, pasture restoration provides the biggest opportunity for reducing emissions in the region.

The abatement potential (AP) for pasture restoration is 26.9 Mt CO_2e yr^{-1}, comprising of two components: C sequestration and avoided deforestation, the latter accounting for 96% of this AP. Despite improved pasture productivity, less area is used to meet the

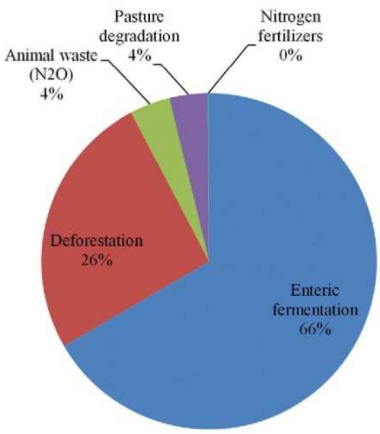

Fig. 2. Share of the main GHG emissions sources from beef production in the Brazilian *Cerrado*. The values relates to the proportion of each source in relation to the accumulated emissions for the period 2010–2030.

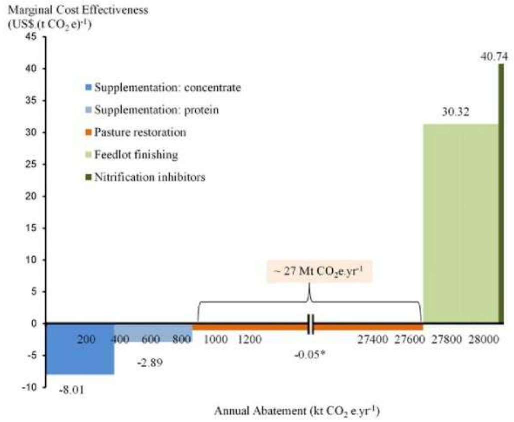

Fig. 3. Marginal abatement cost schedule of key mitigation measures applicable to beef production in the *Cerrado*. The abatement potential (x-axis) and cost effectiveness (y-axis) of each measure was calculated as the average values obtained by adopting the measure over the 2006–2030 period. The figures are average values for the period of 2006–2030. * Not in scale.

same demand relative to the baseline, what means forage availability optimally matches that required for demand. In a scenario of increased forage productivity and higher beef demand, methane emissions would rise as result of increased animal numbers. Pasture restoration would improve the *Cerrado* average productivity from 10 to 11.2 t DM ha^{-1} yr^{-1}, an increase of 12% relative to the baseline. This increase would lead to an average C sequestration rate of 0.32 t CO_2e ha^{-1} yr^{-1}. This is a low C uptake potential when compared to values found by Maia et al. (2009), which showed that C sequestration rates of 2.24 t CO_2e ha^{-1} yr^{-1} can be achieved in well-managed pastures in *Cerrado*. The carbon sequestration rate however, reflect the 2006–2030 period, after which, and in the long term, as pastures are intensified it will eventually reach equilibrium and therefore no more carbon is likely to be sequestered.

The AP of feedlot finishing is 440 kt CO_2e yr^{-1}, but the measure cost-effectiveness US$ 31.32 t CO_2e^{-1} is high relative to supplementation.

Nitrification inhibitors are the least cost-effective measure considered. But this analysis only considered the application to N used for pasture and crops fertilization and excluded the application to animal excreta.

The results indicate that restoring degraded lands is the biggest opportunity for reducing emissions in the *Cerrado*. The AP of this measure is about 20 times greater than all the other measures combined.

An important assumption underpinning the MACC relates to the assumed measure adoption rates (Table 5). With exception of feedlot finishing, the adoption rates are optimised, meaning the rates that maximizes the gross margin in the model.

Table 5
Mitigation measures adoption rate.

Mitigation measure	Adoption rate	Unit
Supplementation: concentrate	12	%[a]
Supplementation: protein	2.2	%
Pasture restoration	314.7	10^3 ha yr^{-1}
Feedlot finishing	15	%
Nitrification inhibitors	12.78	g ha^{-1} yr^{-1}

[a] Adoption rates for feedlot, protein and concentrate supplementation are calculated as the percentage of the total finished animals. The adoption rate of pasture restoration is the annual average area of restored pasture.

5. Discussion

To meet increasing domestic and export demand, the government of Brazil recognizes the need to foster sustainable agricultural intensification, which implies increased resource productivity while minimizing significant domestic and global external costs implicit in GHG emissions and deforestation. The results presented here suggest that a significant contribution to this objective can be made by targeting specific measures to improve yield. Specifically, pasture restoration, supplements and feedlot measures could reduce sector emissions by 24.1% by 2030. Moreover, by adopting only negative-cost measures (Fig. 3), it is possible to abate about 23.7% of baseline livestock emissions in the *Cerrado*, up to 2030. According to our results the restoration of degraded pastures offers the greatest abatement potential, involving the restoration of an average of 314.7×10^3 ha yr^{-1} in *Cerrado* grasslands.

Currently, it has been estimated that 50% to 80% of pastures in the Amazon and *Cerrado* are degraded (Macedo et al., 2014; Peron and Evangelista, 2004). Achieving a higher rate is likely to entail some initial investment costs to promote modified production practises and this is the purpose of the government's ABC programme. ABC is an ambitious plan created to stimulate farmers and ranchers to adopt mitigation measures including restoration of degraded pastures, helping the country to meet the reduction targets presented at COP 15. ABC is the biggest sustainable agriculture fund running in Brazil, with a key objective of disbursing subsidized credit to the agricultural sector. The plan currently targets the recovery of 15 Mha in 10 years, which will lead to reductions up to 104 Mt CO_2e, roughly 64% of the programme total mitigation potential. But it does not include other relevant measures such as feed supplementation measures, which would normally be considered as privately profitable anyway.

The outcome of the ABC plan remains to be evaluated, but initial indications suggest that uptake of credit has been slower than anticipated (Claudio, 2012). Recent evidence from the Amazon Environmental Research Institute suggests that several institutional barriers have retarded the programme, including a lack of publicity and information about the aims and the benefits of the programme, difficulties in complying with programme requirements, a lack of technical assistance, and producer scepticism about the private economic benefits of measures that are predominantly designed to address global external costs (Stabile et al., 2012).

Producers also perceive transaction costs in programme compliance and a lack of basic infrastructure (Rada, 2013) that is needed to support increased productivity. In short, the ABC plan is confronting similar behavioural barriers in relation to non-adoption, identified in other mitigation studies, e.g. Moran et al. (2013), which need to be addressed before wider measure adoption can be expected.

6. Conclusion

This paper highlights how resource efficiency measures can be enacted (notionally within farm gate) in the *Cerrado* biome to help reconcile competing objectives of private yield improvements and the reduction of external costs. The analysis responds to the need to demonstrate the possibilities for sustainable intensification, allowing Brazil to meet economic growth ambitions for the sector.

The key finding from the use of the economic optimisation model is the representation of the cost-effectiveness of key mitigation measures. Specifically, that pasture restoration is the most promising mitigation measure in terms of abatement potential volume and that it offers a cost saving for the livestock sector. By adopting these measures – pasture restoration, concentrate and protein supplementations – the *Cerrado* could reduce 23.7% of its emissions by 2030, while the total abatement potential of adopting all measures is 24.1%.

The analysis presented here has a number of caveats that potentially warrant further research. These include a more detailed representation of the biophysical heterogeneity of the *Cerrado* biome, more detailed treatment of the deforestation (and hence land sparing) processes and relaxation of the assumed equilibrium supply and demand conditions in the optimisation model.

Nevertheless by highlighting cost-effective policy options, this paper contributes to our understanding of sustainable intensification processes as relevant to Brazilian livestock production.

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Appendix. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.agsy.2015.08.011.

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Appendix 3: paper 2

De Oliveira Silva, R., Barioni, L.G., Hall, J.A.J., Folegatti Matsuura, M., Zanett Albertini, T., Fernandes, F.A., Moran, D., 2016. Increasing beef production could lower greenhouse gas emissions in Brazil if decoupled from deforestation. Nat. Clim. Chang. 6, 3–8. doi:10.1038/nclimate2916

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LETTERS

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Increasing beef production could lower greenhouse gas emissions in Brazil if decoupled from deforestation

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Recent debate about agricultural greenhouse gas emissions mitigation highlights trade-offs inherent in the way we produce and consume food, with increasing scrutiny on emissions-intensive livestock products[1-3]. Although most research has focused on mitigation through improved productivity[4,5], systemic interactions resulting from reduced beef production at the regional level are still unexplored. A detailed optimization model of beef production encompassing pasture degradation and recovery processes, animal and deforestation emissions, soil organic carbon (SOC) dynamics and upstream life-cycle inventory was developed and parameterized for the Brazilian Cerrado. Economic return was maximized considering two alternative scenarios: decoupled livestock–deforestation (DLD), assuming baseline deforestation rates controlled by effective policy; and coupled livestock–deforestation (CLD), where shifting beef demand alters deforestation rates. In DLD, reduced consumption actually leads to less productive beef systems, associated with higher emissions intensities and total emissions, whereas increased production leads to more efficient systems with boosted SOC stocks, reducing both per kilogram and total emissions. Under CLD, increased production leads to 60% higher emissions than in DLD. The results indicate the extent to which deforestation control contributes to sustainable intensification in Cerrado beef systems, and how alternative life-cycle analytical approaches result in significantly different emission estimates.

Rising global population combined with shifting dietary preferences in emerging economies is leading to a significant increase in the demand for livestock products, which is expected to double by 2050 (ref. 2). This shift is happening in the context of global climate change and associated resource scarcities, leading to calls for sustainable agricultural intensification (SAI; refs 3,5,6). Although a contested concept, the SAI debate highlights elements of resource use efficiency in production, combined with the management of demand or consumption[3,7,8]. Although persuasive, the SAI literature is limited in its illustration of the environmental and economic trade-offs that can emerge when implementing SAI measures in globally significant production systems.

Ruminant livestock is specifically implicated as a major cause of agricultural externalities in terms of greenhouse gas (GHG) emissions (CH_4 and N_2O) and appropriation of land that otherwise provisions other valuable ecosystem services[5]. A counter-argument suggests that grass-fed beef systems have significantly lower emissions when accounting for atmospheric carbon dioxide (CO_2) uptake by deep-root grasses promoting greater soil carbon (C) storage. Such systems could play a significant role in stabilizing GHGs (ref. 9). Moreover, this sequestration in specific systems may offset direct livestock emissions[9].

Brazilian livestock production accounts for 8.3% of global consumption[10] and the sector aims to capitalize on growing demand. However, related emissions are significant in the national GHG total including those related to deforestation. If both beef demand and target deforestation rates are to be met, while also reaching ambitious GHG mitigation targets, further productivity growth will be required. Alternatively, product demand or consumption may need to be managed[3,7].

This study focuses on the central savannah (Cerrado) core (Fig. 1), an area accounting for approximately 34% of Brazilian beef production[11]. Considered part of the Brazilian agricultural frontier, the Cerrado is credited as the driver of the country's ascendance in global agricultural commodity markets[12,13]. Around 90% of Brazilian livestock are solely grass-fed (mainly tropical grasses of the genus *Brachiaria*). Several studies show that improving tropical grasses productivity results in increased soil carbon stocks[14,15], with net atmospheric CO_2 removals of almost $1\ Mg\,C\,ha^{-1}\,yr^{-1}$ (ref. 14) when comparing degraded and improved pastures under a standard Intergovernmental Panel on Climate Change method[16].

The analysis quantifies the relationship between beef demand, production intensification, deforestation and soil carbon dynamics, indicating how deforestation rates influence emission intensities. We employed a linear programming model (Methods and Supplementary Methods) representing Cerrado beef production subject to market demand and pasture area scenarios. The model combines economic and bioeconomic variables to optimize farm resource allocation, including the adjustment of intensification levels through the representation of pasture degradation and restoration processes. It estimates GHG emissions—including direct animal emissions (Supplementary Table 1), changes in SOC, plus loss of biomass through deforestation, and life-cycle assessment (LCA) data covering inputs and farm operations used to maintain and recover pasture, and crop production, the latter used to formulate animal feedlot rations (Supplementary Table 2).

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Figure 1 | Brazilian central Cerrado (shaded).

As there are no published biome-specific beef demand projections in Brazil, baseline demand (D_{BAU}) is assumed to be proportional to the whole-country projected demand, that is, exports plus domestic consumption[17].

We compared the accumulated emissions 2006–2030 under two land use scenarios: the decoupled livestock–deforestation (DLD) scenario, where the same baseline pasture area projection (A_{BAU}) associated with the baseline demand is used for all demand scenarios (that is, the same deforestation projections irrespective of consumption levels); and the coupled livestock–deforestation (CLD) scenario, in which deforestation projections are sensitive to variations in demand. In both scenarios, intensification occurs only by pasture restoration promoting improvements in forage productivity through mechanical and chemical treatment of the soil (Supplementary Methods).

The varied demand scenarios are: $D_{BAU-10\%}$, $D_{BAU-20\%}$ and $D_{BAU-30\%}$, representing decreasing demand/consumption scenarios relative to baseline demand by 2030, and conversely increasing demand scenarios $D_{BAU+10\%}$, $D_{BAU+20\%}$ and $D_{BAU+30\%}$ (Fig. 2a).

Deforestation is assumed exogenous, avoiding the need to model competition between livestock and agricultural land use explicitly. To explore the link between beef demand and deforestation we use a parameter (k) to represent the percentage variation of pasture area in relation to changes in demand. Based on empirical evidence[10,11], estimated k values decreased from more than 0.4 in the early 1970s to zero in the latest available data period (1995–2006; see Supplementary Information). In the CLD scenario we assume the worst case $k = 0.4$, that is, for every 1% variation in demand, pasture area changes by 0.4%, which would generate a deforested area of 10.9 Mha by 2030 relative to 1.5 Mha for the baseline projections (Supplementary Table 3).

In the scenario of controlled deforestation (DLD), the analysis shows that lower than projected beef demand may increase emissions in the Cerrado grazing system as a result of comparatively less efficient systems with higher emission intensities. Lower demand and smaller herds require less grass production, reducing the incentive to maintain or increase productivity; pastures then degrade, losing organic matter and soil carbon stocks. Higher demand combined with effective deforestation control policies leads to more efficient systems with lower emissions intensity due to significant increases in carbon uptake by deep-rooted grasses in improved pastures.

Under DLD, emissions increase by 3%, 5% and 9%, respectively for the consumption reduction scenarios $D_{BAU-10\%}$, $D_{BAU-20\%}$ and $D_{BAU-30\%}$. Whereas in $D_{BAU+10\%}$, $D_{BAU+20\%}$ and $D_{BAU+30\%}$, emissions decrease by 3%, 7% and 10%, respectively relative to D_{BAU} (Fig. 2b). Increased cattle emissions in these scenarios are offset by increased grassland carbon sequestration rates. Higher annual demand leads the model to increase productivity by restoring degraded pastures, and more productive pasture is associated with a higher carbon equilibrium value (Supplementary Table 4). Accumulated emissions (2006–2030) range from 1.9 Gt to 2.3 Gt of CO_2e, respectively for $D_{BAU+30\%}$ and $D_{BAU-30\%}$.

This result is undermined by altering the deforestation scenarios. Under CLD and assuming that pasture expansion responds to changes in demand as in the 1970s, accumulated emissions (2006–2030) from beef production would range from 2.1 Gt to 3.0 Gt of CO_2e, respectively for $D_{BAU-30\%}$ and $D_{BAU+30\%}$; that is, emissions would be 60% higher than in DLD for the same demand scenario $D_{BAU+30\%}$. The analysis shows that under both $D_{BAU-10\%}$ and $D_{BAU-20\%}$, emissions decrease by 6%. Under the $D_{BAU-30\%}$ scenario emissions are reduced by 2%, relative to D_{BAU}. Under $D_{BAU+10\%}$, $D_{BAU+20\%}$ and $D_{BAU+30\%}$, emissions increase 12, 28 and 44%, relative to D_{BAU} (Fig. 2c). The changes are mainly due to direct animal emissions and deforestation. Note that the increasing demand scenarios drive proportional increases in deforestation, but under decreasing demand scenarios deforestation cannot be less than zero. In fact, for $D_{BAU-30\%}$, $D_{BAU-20\%}$ and $D_{BAU-10\%}$, deforestation rates are insignificant in relation to baseline figures, making GHG reductions more modest for these scenarios relative to the increases driven by deforestation under increasing demand scenarios.

Sensitivity analysis helps to identity the value of k representing the mid-way between CLD and DLD scenarios; that is, the value where increases in deforestation and cattle emissions would be offset by gains from increased SOC uptake (Fig. 2d). The analysis suggests that this offsetting occurs approximately when $k = 0.1$; that is, only 10% of production increases are due to pasture expansion and therefore 90% are due to productivity gains.

Emissions mitigation by demand-driven intensification in the DLD scenario is space and time dependent. The results depend on specific geographical data and system characteristics of Cerrado production, and SOC is unlikely to be accumulated indefinitely[18]. To estimate the longevity of the inverse demand–emissions relationship (when SOC stocks approach equilibrium content and no longer offset increased animal emissions), we conducted long-term analysis for 125 years. We assumed fixed demand from 2030 to 2130 and observe: the annual net emissions and the changes in accumulated emissions in 10 year periods from 2010 for each demand scenario under DLD. As demand projections increase up to 2030, the assumption of constant demand and area from 2030 leads to stabilized land productivity from 2030 to 2130.

Under the DLD scenario, increases in demand would lead to decreases in annual emissions up to 2057, when the situation inverts (Fig. 3a). However, Fig. 3b shows that in terms of accumulated emissions, reducing beef consumption would lead to decreased emissions around 2120.

Although SOC equilibrium has not been reached by 2057, the average sequestration rate of 0.08 t of C ha^{-1} yr^{-1} (under $D_{BAU+30\%}$) no longer offsets emissions from increased animal numbers. By 2057 SOC stocks reach 60% of the difference between initial stocks and equilibrium values (Supplementary Table 6), that is, 27 years after land productivity is stabilized, which is consistent with experimental evidence[19,20]. (Field experiments in temperate climates suggest a period of 25 years for SOC to reach 50% of the difference between initial and equilibrium values[19]. Experiments in the Amazon report a period of 27 years to reach 60% (Nova vida site[20]).)

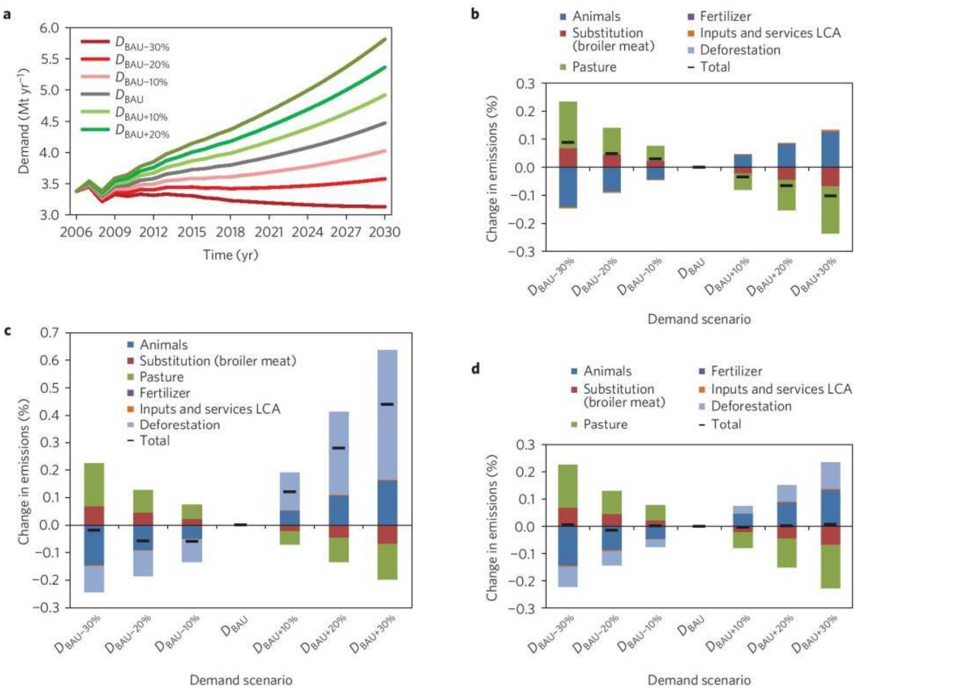

Figure 2 | Demand scenarios and sensitivity analysis. **a**, Cerrado baseline demand (D_{BAU}) and varied demand projections that correspond to percentage variation by 2030 in relation to D_{BAU}. **b–d**, Percentage changes in accumulated emissions (2006–2030) as a function of demand scenarios under the DLD scenario (**b**), the CLD scenario (**c**), and an intermediate scenario with $k = 0.1$ (**d**). The analysis assumes that beef consumption is substituted by broiler meat (Supplementary Table 5) and accounts for the net change in production emissions arising from this substitution.

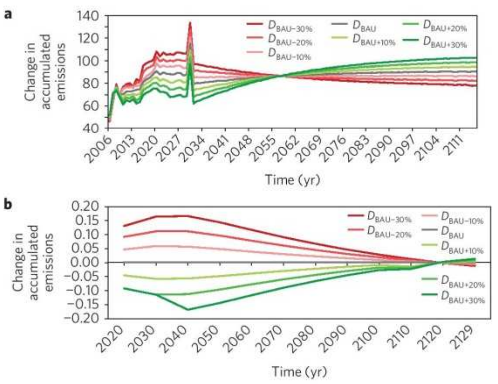

Figure 3 | Long-term GHG emissions analysis for the demand scenarios. **a**, Annual net GHG emissions. **b**, Percentage changes in accumulated GHGs. Note that the emissions peak in 2030 (**a**) is due to high deforestation rates in that year in the baseline projections employed[17].

Our results implicitly show significant changes in emissions intensity depending on demand scenarios and deforestation. The lowest value (18.1 kg of CO_2e per kg of carcass weight equivalent (CWE)) is observed under DLD and D_{BAU+30}, which uses the least area to produce most beef (Fig. 4a). Under the CLD scenario, the lowest value is found in the baseline demand (22.2 kg of CO_2e per kg of CWE), but emissions intensity could reach 31.0 kg of CO_2e per kg of CWE under $D_{BAU+30\%}$, around 40% of this being due to deforestation (Fig. 4b).

The analysis contributes to the SAI debate by highlighting the potentially inverse relationship between consumption and emissions that may be found in a globally significant beef production system.

A key factor in the results is how deforestation responds to changes in beef demand (parameter k). In the increasingly likely scenarios of controlled deforestation, the analysis shows that lower than projected beef demand may increase emissions in the Cerrado grazing system owing to comparatively higher emission intensities.

Empirical evidence supports the DLD scenario by showing a calibrated value of $k = 0$ (see Supplementary File). Since 2005, data show an apparent decoupling of cattle herd sizes and deforestation in Amazonia and Cerrado, replacing a historic correlation over the period 1975–2005; a trend attributed to a combination of supply and demand side factors including intensification in large-scale commodity-oriented farming, market regulation (for example, moratoria on beef and soy grown in recently opened areas), product certification, and more effective law enforcement[21–23].

Recent studies indicate that current global trends in livestock productivity will not accommodate future projected global demand[1]. This result adds to evidence that Brazil in particular has

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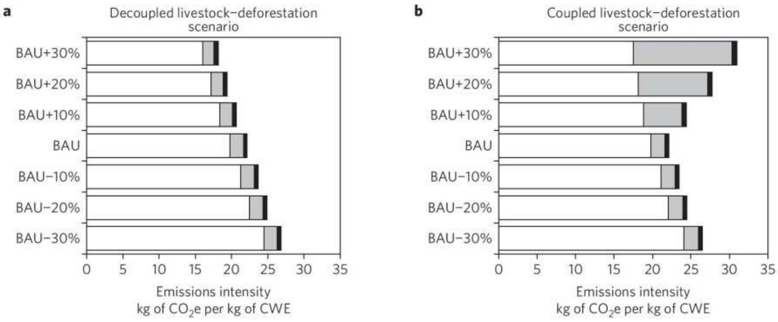

Figure 4 | Emissions intensity analysis. a, Emissions intensity as a function of demand scenario for the decoupled livestock-deforestation scenario. **b**, Emissions intensity as a function of demand scenario for the coupled livestock–deforestation scenario. Carbon footprint calculated as the average value from 2010 to 2025, showing the sum of farm emissions: animals and pasture (emissions by degradation or carbon sequestration and nitrogen fertilizers nitrification; white), deforestation emissions (grey) and LCA emissions from inputs and farm operations used to restore pastures and changed land use (for example, fertilizers, seeds and machinery operations; black).

enough land to meet demand for food and energy at least until 2040 without further natural habitat conversion[17,24]. In fact, under DLD the highest average stocking rate in the model, 1.33 head ha^{-1} (under $D_{BAU+30\%}$), is below the 2 head ha^{-1} carrying capacity associated with negative climate impacts[24].

The analysis also indicates that restoration of degraded pastures is the biggest opportunity for national mitigation plans; indeed, after avoided deforestation, the restoration of 15 Mha nationwide from 2010 to 2020 is the main measure contributing to the 40% reduction target by 2020 (ref. 25).

As the analysis employs a consequential LCA approach (also called 'market based' LCA, which is able to capture changes in emissions in response to changes in product demand and political decisions), it contrasts with other results[1,2,26] using attributional analysis based on constant emission intensity irrespective of consumption level.

More generally our results reflect Cerrado system-specific data, and the picture might differ if we analyse other regions of Brazil or worldwide. The Cerrado is nevertheless seen as a model for transforming other global savannahs[27].

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

R.d.O.S., L.G.B. and D.M. designed the study and wrote the paper, R.d.O.S. and L.G.B. developed the mathematical model, R.d.O.S. implemented the model and generated the results, J.A.J.H. contributed to the model development and mathematical solutions, M.F.M. provided the LCA data, T.Z.A. provided the bioeconomic data, and F.A.F. performed the simulations with the CENTURY model.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.d.O.S.

Competing financial interests

The authors declare no competing financial interests.

LETTERS NATURE CLIMATE CHANGE DOI: 10.1038/NCLIMATE2916

Methods

EAGGLE model. The analysis employed the EAGGLE (Economic Analysis of Greenhouse Gases for Livestock Emissions) model (Supplementary Methods), a bottom-up multi-period linear programming model that simulates beef production systems in Brazil subject to demand and pasture area. The model maximizes farm profit by optimally allocating resources, including the adjustment of pasture intensification levels according to bioeconomic parameters, and estimates the GHGs—including changes in soil carbon stocks—for a production period.

GHG emissions sources. EAGGLE estimates GHGs using emissions factors for direct emissions and life-cycle assessment (LCA). GHG emissions 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 Cerrado deforestation (due to loss of natural vegetation); (e) CO_2 from pasture degradation and land use change from pasture to crops; and (f) LCA factors for inputs and farm operations applied in land use change and restoration practices (Supplementary Table 2). Items (a) and (b) depend on herd composition: each age cohort of males and females (heifer or cow) has an associated emission factor of CH_4 and N_2O calculated using Tier 2 methodology[16] (see values in Supplementary Table 1). Owing to the lack of studies for Brazilian conditions, for (c) we used the Tier 1 Intergovernmental Panel on Climate Change default factor of 1% (ref. 16). The emissions from (d) are calculated using a coefficient of loss of natural vegetation per hectare of deforested area, estimated as 34.6 tons of C per hectare[28]. For (e), the emissions are calculated according to the section Soil organic carbon dynamics (Supplementary Methods).

Soil carbon stocks. Depending on the dry matter productivity level, the C flux may change significantly. The EAGGLE model works with equilibrium values of the C stock for each type of pasture and crop. The higher the pasture productivity, the higher the C equilibrium value (see Supplementary Table 4). Equilibrium values and the time to reach equilibrium were calculated exogenously, using simulations from the CENTURY model[29] applied to Cerrado biophysical characteristics and using the annual dry matter productivity calculated for each pasture category.

Demand and pasture area data. Projections from The World Bank[17] were used for both pasture area and beef demand. The projections correspond to the period 2006–2030. Historical data from 2006–2013 were used to validate the employed demand projections (Supplementary File). For pasture area projections, the last observational data were in 2006 (last agricultural census).

We assume Cerrado pasture area and beef demand share are a fixed proportion of the national projections—because there are no biome-specific predictions in the literature. The Cerrado pasture area represented around 34% of the national total in 2006 (when the last agricultural census[11] was undertaken). We therefore assume that Cerrado pasture area corresponds to 34% of Brazil's pasture area projections, and that this proportion is constant during the study period (2006–2030). Similarly, we assume beef demand to be proportional to area; thus, demand for Cerrado output is also equivalent to 34% of national demand. The model is partial with comparative static equilibrium adjustment between demand and supply; that is, each year, production equals demand and prices remain constant for the whole period.

Scenario construction and deforestation. In both coupled livestock–deforestation and decoupled livestock–deforestation scenarios, pasture area and therefore deforestation is exogenous to the optimization model.

The analysis employs baseline pasture area projections from a World Bank study[17]. For the CLD scenario, we estimate changes in deforestation as a function of changes in beef demand by assuming that every change in annual demand in relation to baseline projections would cause a proportional change in annual pasture area:

$$\frac{A_{\mathrm{BAU}+X\%,t}-A_{\mathrm{BAU},t}}{A_{\mathrm{BAU},t}}=k\frac{D_{\mathrm{BAU}+X\%,t}-D_{\mathrm{BAU}}}{D_{\mathrm{BAU}}}\Rightarrow A_{\mathrm{BAU}+X\%,t}$$
$$=\left[1+k\left(\frac{D_{\mathrm{BAU}+X\%,t}}{D_{\mathrm{BAU},t}}-1\right)\right]A_{\mathrm{BAU},t}$$

where $A_{\mathrm{BAU}+X\%,t}$ represents the altered pasture area projections in relation to baseline projections $A_{\mathrm{BAU},t}$; $D_{\mathrm{BAU}+X\%}$ represents the altered demand projection where X is in $[-30, -20, -10, 10, 20, 30]$ and represents the change by 2030; D_{BAU} is the baseline demand; k is the proportional change in pasture area due to changes in demand projections.

For the DLD scenario, the same area projection is used regardless level of consumption (demand scenarios).

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