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EAGGLE: A LINEAR PROGRAMMING MODEL FOR OPTIMIZING MITIGATION STRATEGIES OF GREENHOUSE GASES EMISSIONS IN BEEF CATTLE PRODUCTION SYSTEMS

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Dissertation presented to the Institute of Mathematics, Statistics and Scientific Computing of the University of Campinas in partial fulfillment of the requirements for the degree of Master in Applied Mathematics

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Orientador: Antonio Carlos Moretti

Coorientador: Luis Gustavo Barioni

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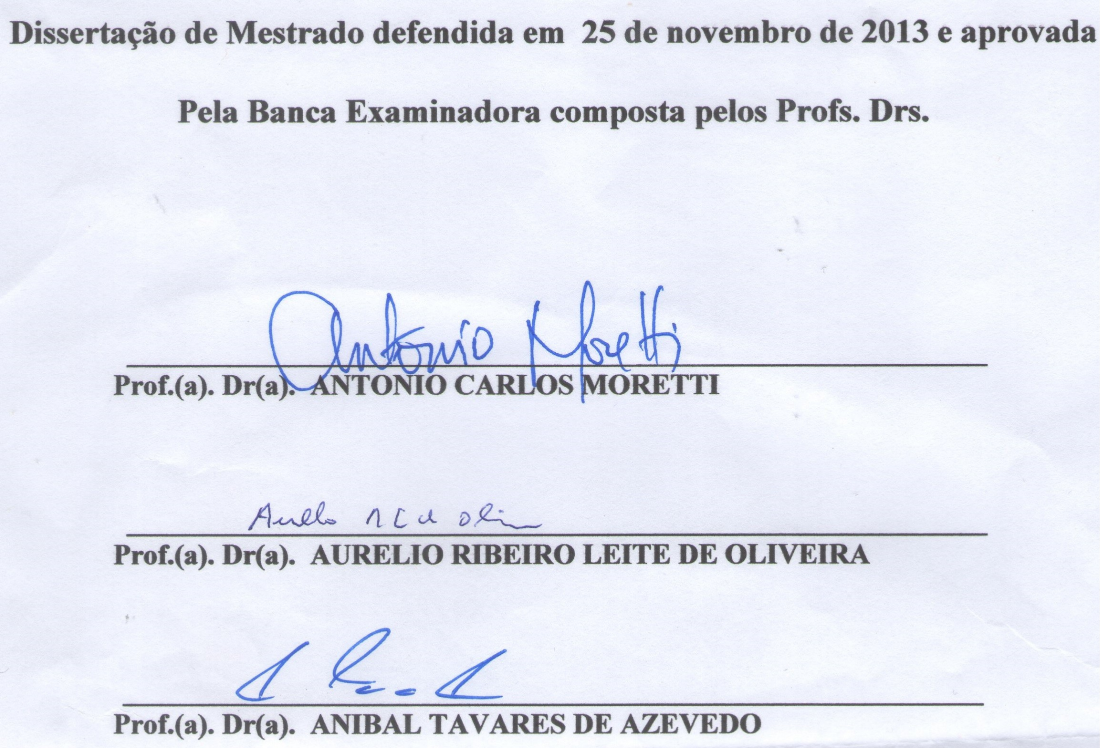

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Prof.(a). Dr(a). AURELIO RIBEIRO LEITE DE OLIVEIRA

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Abstract

Brazil is one of the first major developing countries to commit to a national emissions target that requires a reduction of between 36.1% and 38.9% relative to baseline emissions by 2020.

Focusing on the *Cerrado* core (Central Brazilian Savanna), responsible for about 35% of the country's beef production, this study estimates the region GHG emissions from 2006 to 2030. This work also investigates the cost-effectiveness of the GHG abatement potential.

The analysis was made by means of a construction of linear programing (LP) model, coined EAGGLE (Economic Analysis of Greenhouse Gases for Livestock Emissions). The LP model represents a beef production system under grazing and feedlot finishing. A second model was developed to estimate the C stocks under pastures soils with different dry-matter productivity. In this model it is simulated the effects of degradation, maintenance, restoration end the land use change dynamics over the C stocks.

As a baseline, the region is going to emit 1.2 Gt from 2010 to 2020, the equivalent of 8% of the country´s total liquid emissions. A set of mitigation measures, applicable to Brazil, were analyzed by constructing a marginal abatement cost curve (MACC). The results show that by 2030 the region could reduce emissions by 24.3 MtCO2e.yr^{-1} with negative costs; while total abatement potential shown by the MACC is 24.7MtCO2e.yr^{-1}.

Pasture restoration, involving avoided deforestation, offers the largest contribution to these results. Sensitivity analysis is used to evaluate the abatement potential of pasture restoration against variations in beef demand. Counterintuitively, the results showed, if demand projections decreases by 10%, 20% or 30% until 2030, the total liquid emissions for the period increases 1%, 4%, and 5%, in GWP, respectively. Whereas increasing demand projections by 10%, 20%, and 30% until 2030, there will be a reduction of 2%, 3% and 4% in total liquid GHG emissions for the period. This suggests that PR is able to offset the cattle direct emissions of CH_4 and N_2O by boosting carbon soil sequestration rates.

Keywords: linear programming, pasture restoration, greenhouse gases, livestock, mitigation measures.

Resumo

O Brasil é um dos primeiros países em desenvolvimento a se comprometer com metas de redução das emissões de gases de efeito estufa (GEE). As metas estabelecidas requerem uma redução entre 36,1% a 38,9% relativos às emissões estimadas para 2020.

Focando na região central do Cerrado, responsável por cerca de 35% da produção total de carne bovina do Brasil, este estudo estima as emissões totais de GEE de 2006 a 2030. O estudo também identifica o custo efetivo do potencial de redução das emissões. A análise foi feito por meio da construção de um modelo de programação linear, batizado de "EAGGLE" (Análise Econômica dos Gases de Efeito Estufa das Emissões da Pecuária), que representa um sistema de produção de gado de corte a pasto, com e sem suplementação, e confinamento. Um segundo modelo foi desenvolvido para estimar os estoques de carbono no solo sob pastagens com diferentes níveis de produtividade. Neste modelo é simulado o efeito da degradação, manutenção, recuperação, e dinâmica de mudança de uso da terra nos estoques de carbono. Os resultados mostraram que, no cenário de referência, a região vai emitir cerca de 1,2 Gt de CO_2 entre 2010 a 2020, o que equivale a 8% das emissões líquidas totais do país. Um conjunto de tecnologias de mitigação de GEE, foram analisados através da construção de Curvas de Custo de Abatimento Marginal (CCAM). Os resultados indicam que até 2030, a região é capaz de reduzir as emissões em 24,3 Mt de CO_2 equivalente por ano (CO_2e/yr), utilizando tecnologias com custo efetivo negativo, enquanto que o potencial de redução total apresentado pelas CCAM é 24.7MtCO2e.yr^{-1}. Uma análise de sensibilidade foi feita para avaliar o potencial de mitigação da recuperação de pastagens em função de variações na demanda por carne. Ao contrário do que poderia se esperar, os resultados mostraram que, se as projeções de demanda diminuírem em 10%, 20% ou 30 %, até 2030, as emissões totais para o período aumentam em 1%, 4% e 5%, em GWP, respectivamente. Em contrapartida, considerando que as projeções de demanda cresçam em 10%, 20%, ou 30%, até 2030, haverá uma redução de 2%, 3 % e 4% do total das emissões de GEE, respectivamente. Isto sugere que a recuperação de pastagens é capaz de compensar as emissões diretas de CH_4 e N_2O pelo gado brasileiro, devido ao aumentando das taxas de sequestro de carbono do solo.

Palavras chave: programação linear, recuperação de pastagens, gases de efeito estufa, pecuária, tecnologias de mitigação.

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Chapter 1: Introduction

Brazil has the biggest commercial herd in the world, with 212 million of heads and 170 million hectares of pasture (IBGE, 2011). Between the years of 2001 and 2011, the exportation of Brazilian beef grew 400% (USDA, 2012). Forecasts made by the Ministry of Agriculture (2012) estimate a growth of 2.1% per year in the Brazilian beef production for the period of 2011/2012 to 2021/2022, and, according to the same study, the exportations will rise with the same rate. Nowadays, about 140 countries import Brazilian beef (Luchiari Filho, 2006).

On the other hand, it has been increasing concerns about the environmental impacts of livestock production, in particular the effects on global warming (Gouvello, 2010). Without international efforts to mitigate emissions of Green House Gases (GHGs), it is estimated an increasing on the average global temperature by 4 ° C by 2100, which could represent a risk to global food security (IPCC, 2007).

The emissions from the livestock sector are dominated by gases methane (CH_4), produced by enteric fermentation and feces of ruminant animals, and nitrous oxide (N_2O), emitted by the feces, urine and the use of nitrogen-based fertilizers. These two gases are considered for estimating emissions from the agricultural and livestock sector (Ministry of Science, Technology and Innovation, 2012). According to IPCC (2007), CH_4 is 21 times more potent to global warming than carbon dioxide (CO_2), while N_2O is 298 times more potent.

A study made by World Bank (Gouvello, 2010) estimates an increase in the trajectory of GHG emissions by the Brazilian livestock. A significant portion of these emissions are from deforestation due to expansion of livestock production. Deforestation, activity associated with the conversion of natural vegetation or forests into agricultural production or pastures, represents 60% of Brazil's total emissions (Gouvelho, 2010).

In order to reduce environmental impacts of agricultural sector, Brazilian government proposed a list of NAMAS (Nationally Appropriate Mitigation Actions), voluntary actions to reduce emissions from 36.1% to 38.9%, compared to projected emissions by 2020 (Brazil, 2010).

The mitigation targets can be achieved with the adoption of GHG mitigation technologies, such as pasture recovery, supplementation of animals grazing systems, feedlot finishing, crop-livestock integration, among others.

In order to encourage the implementation of such technologies, the government created the Low Carbon Credit Program (ABC Program) (Brazil, 2010), through which it is offered credit at low interest rates (5.5% per year) to producers who adopt some of the technologies proposed by the program. Brazil's total emissions for 2020 were estimated at 3.2 billion tons of CO_2 equivalent (CO_2e). The prediction of the program is to restore 15 million hectares and reduce between 83 and 104 million tons of CO_2e.

In this context, there is an immediate demand for studies capable to estimate the potential of reduction and the effective cost of mitigation technologies – which will determine the success in achieving targets for voluntary reduction stipulated by the Brazilian government, as well as the success of the ABC Program.

In a similar situation - achieving targets of GHG emissions to a given reference year - Moran et. al. (2010) identified the potential for carbon abatement for the UK as well as the identification of the most promising technologies for mitigation of greenhouse gas emissions. Moran et. al. opted for using Marginal Abatement Cost Curves (MACC), the methodology used for the first time in 70' s, after the crisis in petroleum prices. The goal was to reduce the consumption of petroleum and later, the electricity consumption (Farugui et al., 1990, Jackson, 1991). A MACC for carbon emissions graphically represents the effective marginal cost of emissions reduction (R$.t CO_2e^{-1}) and the potential for reducing emissions (t CO_2e) of different intervention options, ordered by the abatement cost.

Recently the carbon MACCs have become quite popular as a tool for public policy formulation. McKinsey and Company (2009) analyzed the global potential of carbon reduction across different sectors of the economy, including agriculture. Schulte & Donnellan (2012), in a similar study for Ireland, showed that the agricultural sector of the country could reduce projected emissions for 2020 by 6%, using only technologies with negative marginal cost, ie, technologies which while reducing emissions still increase profitability.

Among the various approaches for the construction of MACC, as the use of macro economic equilibrium models and empirical models, it has been highlighted "bottom-up" methodologies, in which are employed more robust models (Macleod et. Al., 2010), with this approach, the potential for carbon abatement and the technologies costs are modeled individually, including possible interactions between technologies. In general, for this modeling work, Linear

Programming (LP) models are used (Dantzig, 2003). These models maximize profit, or gross margin of the productive system, with attendance of demand constraints and specific constraints of the evaluated system. GHG emissions are calculated endogenously in the model.

In this context, this work proposes a study able to identify the GHG mitigation potential of

Brazilian livestock, since the direct emissions summed with deforestation, usually attributed to the activity, may represent a threat to exports of Brazilian cattle (Alvez, 2012)

The study was made by developing the Linear Programming (LP) model, EAGGLE (Economic Analysis of Greenhouse Gases for Livestock Emissions). Exogenously to the LP model, it was incorporated a soil carbon sequestration model. According to reports from FAO (2006), the soils under pastures are able to become one of the biggest land drains of atmospheric CO_2, due to the C uptake by the accumulation of organic matter in the soil, becoming, therefore, keystones to the estimative of the balance between emissions and removals of greenhouse gases GHG by the livestock sector.

Chapter 2: Model overview

2.1 Modeling assumptions and data

Measure cost-effectiveness can be assessed by means of a Linear Programming (LP) model that maximizes the gross margin of a beef cattle production region, considering:

I. herd dynamics;
II. financial resources;
III. feed budgeting;
IV. pasture recovery dynamics, and;
V. soil carbon(C) stock dynamics.

The activities related to animals and financials (I, II, III) are modeled using monthly time steps, (IV) and (V). The ones related to land use and land use change and C stocks are modeled using annual time stepped variables. The *Cerrado* region is modeled as a single farm, with three different products: Nellore cattle, male or female, finished in a grazing system, or a Nellore male finished in a feedlot system (in Brazil, in general, only males are confined). Nellore animals are divided into nine categories, each with an associated weight, death rate, prices and dry-matter (DM) intake.

Table 1: Animals age cohorts, death rate, DM intake, weight, and emissions factors (IPCC, Tier 2).

			Nellore Steer				
Age cohort (*ks*)	Age, months	Death rate ($\%.\text{mth}^{-1}$)	Avg SBW, kg	DMI, kg/day	CO_2e, $\text{kg.head}^{-1}.\text{mth}^{-1}$	Price ($\text{R\$2012.head}^{-1}$)	Maintenance Cost ($\text{R\$2012.head}^{-1}$)
1	[6,9)	0.42	189	5.18	74.28	658	2.1
2	[9,12)	0.42	222	5.84	83.82	691	2.4
3	[12,15)	0.2	255	6.48	92.94	802	2.7
4	[15,18)	0.2	289	7.12	102.02	913	3.0
5	[18,21)	0.2	322	7.72	110.66	1044	3.3
6	[21,24)	0.2	355	8.30	119.09	1158	3.6
7	[24,27)	0.03	388	8.88	127.30	1271	3.9
8	[27,30)	0.03	421	9.44	135.28	1411	4.1
9	[30,33)	0.03	454	9.99	143.26	1526	4.4
Age cohort (*kh*)			Nellore Heifer				
1	[6,9)	0.06	156	4.42	63.46	639	1.5
2	[9,12)	0.06	183	4.98	71.43	626	1.9
3	[12,15)	0.06	210	5.52	79.20	758	1.4
4	[15,18)	0.06	237	6.05	86.76	800	3.5
5	[18,21)	0.06	264	6.56	94.08	987	2.9
6	[21,24)	0.06	291	7.05	101.18	1038	2.5
7	[24,27)	0.06	318	7.54	108.05	1091	3.8
8	[27,30)	0.06	345	8.01	114.92	1142	2.6
9	[30,33)	0.06	372	8.48	121.58	1142	2.6
Breeding stage (*kc*)[2]			Nellore Cows and Calves				
Pregnant	[24,96]	0.06	450	7.69	111.02	1142.16	10.25
Lactation	[24,96]	0.06	450	10.85	155.35	1142.16	3.78
Non-lactation	[24,96]	0.06	400	6.48	93.83	1142.16	3.79
Calf	[0,6)	0.49	36	1.03	0.00	1142.16	1.64
Age cohort (*FL*)			Feedlot Nellore Steers				
FL	[21,24]	0.03	441	11.42	83.18	1635	22.47

The gross margin is modeled with monthly steps. It is given by the incomes, from the sale of animals for slaughter (age cohort 9): 454 kg for males, and 372 kg for females; the outcomes, composed by farm and animals maintenance costs, restoration and land use change costs. The LP model simulates animal growth and optimally defines the partition of animals to be finished by grazing or in a feedlot system. In addition, Nellore heifers can be assigned to breeding or be kept in pasture to be finished. Figure 1 illustrates the main herd dynamics flows represented in model:

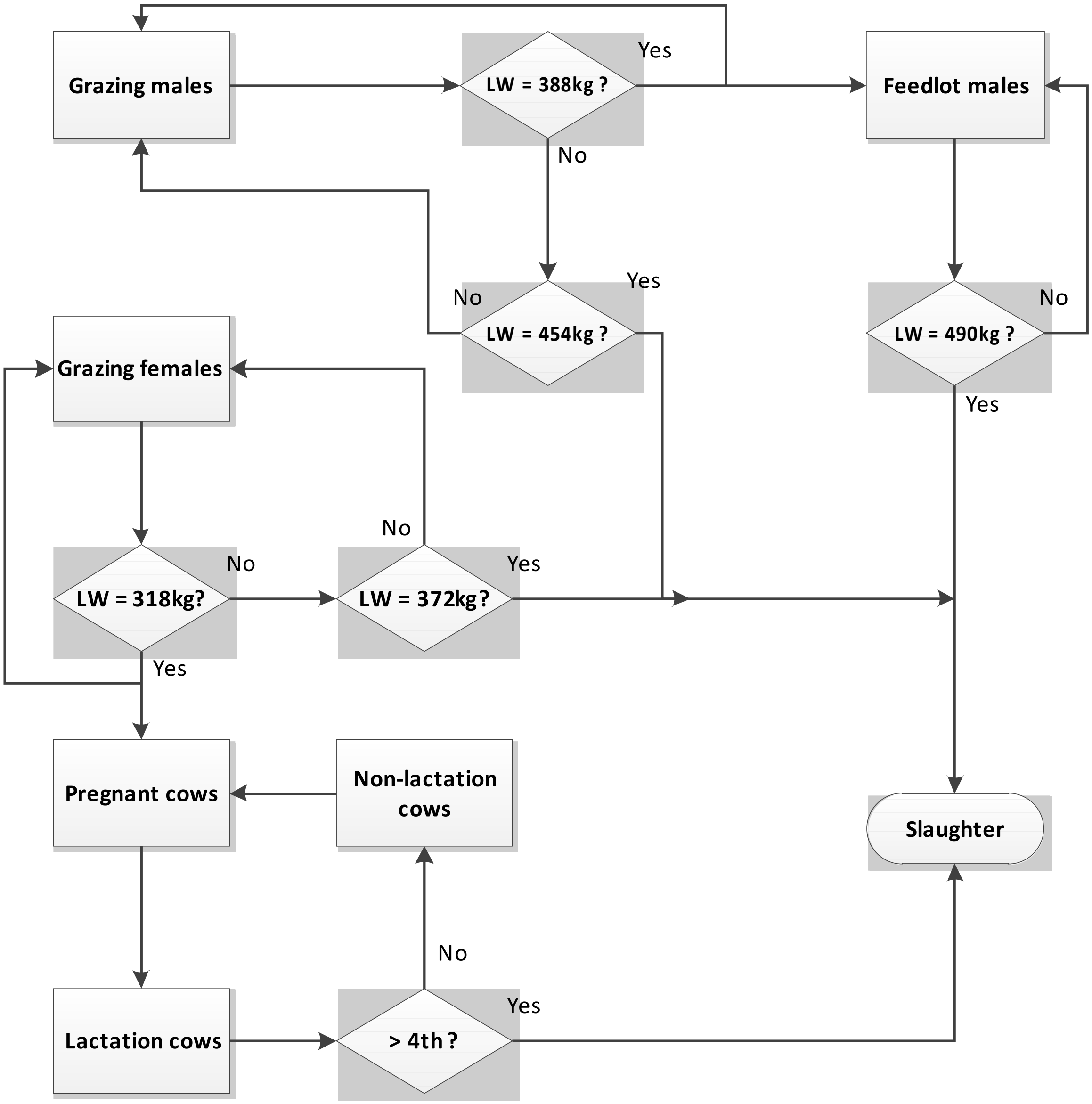

Figure 1: Model´s baseline diagram. It represents the grazing, feedlot and breeding decisions structure.

Cows stay pregnant for nine months and, after calving, lactate for six months. The model was set for a calving interval of eighteen month, so cows are non-lactating and non-pregnant for three months. Cows are slaughtered after weaning their 4th calf.

Calves are assigned to the grazing subsystem (parameters set to represent *Brachiaria bizantha cv Marandu* pastures*)* as soon as they are born. Female calves grow until they reach 318 kg of live weight (LW). At that weight, the model decides the proportion of females allocated to the breeding subsystem or to the finishing system, where they are slaughtered at 372 kg LW.

A proportion of male calves, in the grazing system, can be assigned to the feedlot subsystem when age cohort LW is equal 388kg (i.e. age cohort 9, Table 1). Feedlot time lasts for two months, at which time males about 490kg LW are slaughtered. Males not assigned to feedlots stay grazing and are slaughtered at 454 kg.

The region maintenance costs comprise animal's non-feed and equipment depreciation, amounting to R$ 48.82 $ha^{-1}.yr^{-1}$(2012). Six pastures types {A, B, C, D, E, F} were defined to represent pasture degradation and restoration dynamics. These pastures comprise the same species with different levels of productivity (Table 2). The pasture types productivity was calculated exogenously using the forage DM productivity model publish by Tonato et. al. (2010). It was used Cerrado´s climate and soil type specific data and a set of inputs. The amount of inputs applied, e.g., nitrogen (in the form of urea), limestone, micronutrients, forage seeds (*Brachiaria Brizantha*), and machinery services produces a corresponding DM productivity. The amount of inputs and actions to produce the pasture types {A, B, C, D, E, F} are considered as the necessary application from a degraded pasture (pasture F). The cost to produce pasture A, from a degraded pasture F is the sum of necessary inputs to generate pasture A DM productivity – simulated using Tonato et. al. model.

The model also produces crops: corn, for silage and grain production, and soybeans. Therefore the model generates trajectories for land use (LU) and land use change (LUC) across the set {A, B, C, D, E, F, Corn (grain), Corn(Silage), Soybeans}. The crops are exclusively produced for ration formulation used in the feedlot finishing - and the supplementations (mitigation measures), i.e, crops does not generates direct revenue. The costs of the types of pasture restoration and land plantation of crops (Corn and Soybeans), LULUC were elaborated by experts in the field.

Table 2: Annual dry matter (DM) production and costs of pasture restoration crops plantation and maintenance.

Pasture/Crop	DM ($t.ha^{-1}.yr^{-1}$)	Cost, R\$2012.ha^{-1}	Maintenance (R\$2012/ha)	C stock equilibrium ($Mg.ha^{-1}$)	Sequestration weight (dimensionless)
A	19.6	1278.5	219.6	84.3	0.03015
B	17.6	1063.3	142.0	82.7	
C	12.6	688.9	29.2	62.3	
D	8.7	249.4	18.3	45.2	
E	5.8	72.0	10.9	32.4	
F	3.9	0.0	10.9	26.1	
Corn (Silage)	3.8	4150.8	3185.0	45.0	
Corn(Grain)	9.0	2680.9	1917.7	40.0	
Soybeans	2.5	2183.6	1987.7	45.0	

[1] Costs are composed of applications of urea, limestone, micronutrients, seeds and machinery services.

The total annual pasture area is composition of input data and a decision variable. It is given by the sum of (i) input data, projection from 2006 to 2030, published by Gouvello et. al.(2010), and the (ii) extra deforested area, modeled as decision variable. In other words, besides the annual area is a vector input (Figure 2) for the model, it might expand the area by deforestation, if it is necessary to avoid unfeasibility or if it is economically advantageous.

The pasture area data includes expansion, by deforestation, and compression due to the loss of pasture areas to crops. Besides extra deforestation, the model decides the annual optimal land allocation among the pasture types and crops, for supplementation production. The land allocation dynamics can move area from any land use to another: e.g., F to E, or F to A, or even pasture C to soybeans.

The total dry matter (DM) production is calculated monthly by summing up the product of pasture area and production productivity of each pasture class. The total DM production must be equal to or greater than the grazing animal's intake sum. For the feedlot subsystem, the region has to produce its own feed for the confined animals, so land is allocated for grain and silage production according to the demand for feed by the animals in the feedlot. For simplification, soya and maize (grain or silage) are considered in the diets of feedlot animals.

2.2 Carbon sequestration through pasture management

Pasture management is the main driver for changes in C stock pools. Depending on the level of DM productivity, C flux might change significantly. Assuming similar levels of grazing efficiency, the higher the pasture productivity, the higher the C inputs to the soil. Therefore for each type of pasture in Table 2, a C equilibrium stock is assigned. Nevertheless, the land use might change from one year to another, and thus the stocked C has to be transferred to the other land use. In this sense, the EAGGLE model has a module to account for two types of C fluxes:

(a) **Transferred C**, the C transferred from one land use to another (or from a pasture class to other pasture productivity class). The transference is proportional to the LUC area; product of current C stock per LUC area.

(b) **Capture C**, it is calculated as a function of the distance the current stock is from the equilibrium stock for the land use type. The further from the equilibrium, the higher the C captured. The modeling approach follows the concepts published by Vuichard et. al. (2007).

Chapter 3: Baseline construction

3.1 Beef demand and pasture areas

The baseline scenario was constructed based on forecasts for demand for beef and land for beef production, from 2006 to 2030. These are set out in Brazil´s Low Carbon Case Study (World Bank, 2011). This report uses an econometric estimate of land demand and land use allocation resulting from supply-demand dynamics and geo-referenced spatial model. The beef demand projections used market equilibrium models and estimates domestic demand plus net exports. To estimate the *Cerrado* pasture annual area during the studied period (2006 to 2030), it was assumed the region represents 34% of total Brazil's pasture area, this percentage corresponds to the value in 2006 (Censo, 2006). The *Cerrado* region is responsible for about 35% of the total country's slaughtered animals (ANUALPEC, 2010). So, for simplicity, it was assumed the demand for the region corresponds to the same proportion it represents from total pasture area.

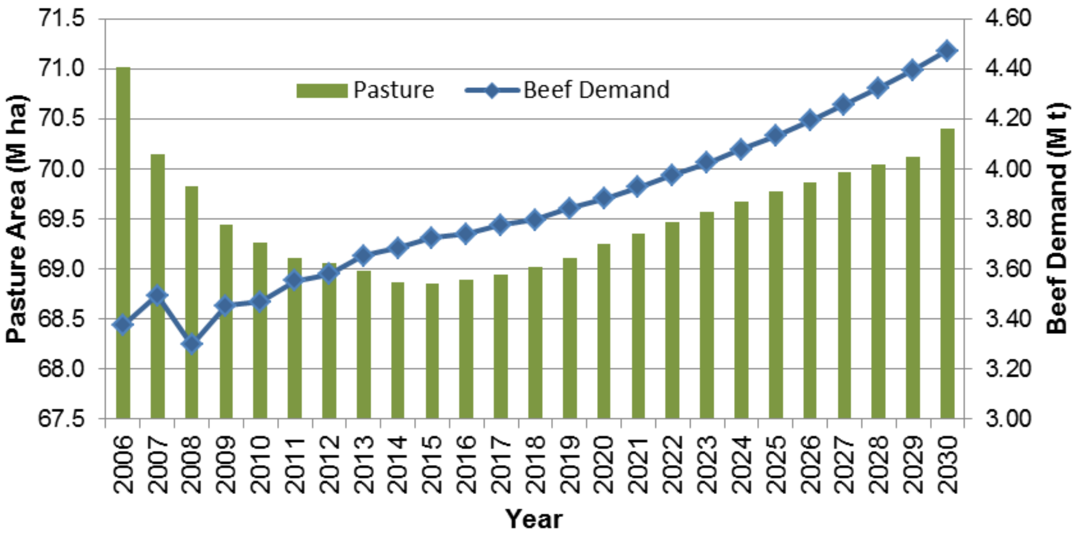

Figure 2: Beef demand and total pasture area projections for Cerrado. Both are assumed as 34% the projections for Brazil, from WB report (2011).

The graph shows that land use for beef production decreases from the 2006 to 2015 due to pasture losses to other production systems. From 2017 there will be an expansion of pasture land, fed by deforestation; achieving 70.4 M ha in 2030. As the baseline represents no intervention in terms of GHG mitigation, pasture restoration (to enhance productivity) was set as a constraint in the model. The assumption in terms of productivity is: no improvement in pasture quality, which means the productivity, was assumed to be the same of 2006's value (10 kg-DM.ha^{-1}.yr^{-1}) throughout the 25 years period.

As seen in Fig. 2, pasture area increased from 2016, which means deforestation. However, as productivity is constrained to be constant in the baseline, the model may open new lands, as it is the only way to increase production. In other words, some deforestation is treated as input to the model, but another extra deforestation (modeled as a decision variable) might be taken due to the productivity constraint. Therefore, in the baseline, production can be increased only by expanding new areas. In this study, deforestation is both input - represented by the annual increment of area, starting from 2017 in Figure 2 - as well as pasture expansion caused by the constant productivity constraint.

About 90% of the Brazilian herd is finished under grazing system (ANUALPEC, 2010), so in the baseline, it is constrained that 10% of the herd in *Cerrado* is finished under feedlot system. To determine the initial pasture composition {A,B,C,D,E,F}, the model was calibrated with a fixed area and beef demand for 30 years, implying in a stabilized solution of the pasture composition with minimum cost.

Chapter 4: Accounted GHG Emissions

4.1 Emissions factors and C stock equilibrium

The GHG commonly associated with the livestock activities are: C dioxide (CO_2); methane (CH_4) and nitrous oxide (N_2O), (IPCC, 2006). These emissions were accounted by using emissions factors (Table 1), associated with the region activities. GHG sources were: (a) CH_4, from cattle enteric fermentation; (b) N_2O from cattle excreta; (c) N_2O from N fertilization; (d) CO_2 from deforestation; and (e) CO_2 from pasture degradation (loss of soil C stock).

The items (a) and (b) depend on the herd composition: each age cohort of males and females (heifer or cow) has an associated emissions factor of CH_4 and N_2O, calculated by Tier 2 (IPCC, 2006). The N conversion into N_2O was assumed as 1%, and emissions from deforestation are account by the loss of 55Mg of $C.ha^{-1}$.

For (e), a C sequestration model was developed. The model accounts for C annual stocks as a function of LU and LUC, based on the C equilibrium stock simulated for the *Cerrado* region using the CENTURY model, Table 2. The C sequestration equations, incorporated in the LP model, accounts for the C stock transferred from one land use to another, deforested area, lost area (to agriculture), and estimates the sequestered C per year based on the distance from the current C stock and the equilibrium stock.

Chapter 5: Mitigation Measures

A set of GHG mitigation measures was selected to be evaluated. The selection criteria were based on literature review and expert opinion on the relevance and applicability of the technologies to Brazilian conditions. The assessed measures in this work are:

- Concentrate supplementation (CS):
- Protein supplementation (PS);
- Pasture restoration (PR);
- Nitrification inhibitors (NI);
- Pasture irrigation (PI);
- Feedlot finishing (FF).

For the pasture restoration measure, the productivity constraint of the baseline scenario was removed. Therefore, in this measure, the model is allowed to increase production not only by expanding pasture area but by improving productivity.

Table 3: Selected livestock mitigation measures.

Mitigation measure	Description	Cost[1]	Unit	Adoption rate modelling
Feedlot finishing	Steers with 388Kg of LW can be selected for feedlot. The confinement takes 2 months. Afterwards, the steers are finished with 490 kg.	17.81	$R\$.au^{-1}$	15% of the total finished animals.
N inhibitors	It is applied 1 kg of Agrotain® per ton of applied N.	120	$R\$.t^{-1}$	100% of all applied N
Pasture restoration	Every year during the production, it is possible to increase productivity.	TABLE 2	$R\$.ha^{-1}$	Optimized
Supplementation concentrate	Steers with 421 kg of LW can be selected for concentrate supplementation. The supplementation takes 2 months and the final weight is 490 kg.	6.00	$R\$.au^{-1}.mth^{-1}$	Optimized
Supplementation protein	Calves (189 kg) can be selected to be supplemented with protein (only in March). The steers are finished after 15 months, with 481 kg.	2.25	$R\$.au^{-1}.mth^{-1}$	Optimized
Pasture Irrigation	Irrigation during the dry months (June to March). Only pasture type A.	23.6	$R\$.ha^{-1}.mth^{-1}$	100% of pastures type A.

Chapter 6: The EAGGLE Model

Table 4: List of indices.

Symbol	Description	Range/value
c	Crops	(Corn(silage), Corn(grain), Soybeans)
i	Land Use	(A, B, C, D, E, F, Corn(silage), Corn(grain), Soybeans)
j	Land Use	(A, B, C, D, E, F, Corn(silage), Corn(grain), Soybeans)
kc	Cows breeding stage	(1, 2, ... , 12)
kh	Heifers age cohort	(1, 2, ... , 9)
ks	Steer age cohort	(1, 2, ... , 9)
m	Month	(1,2,...,M)
$M_{(m)}$	Calendar month equivalent to counted month *m*	(Jan, Feb, ... , Dec)
p	Pasture	(A, B, C, D, E, F)
q	Pasture	(A, B, C, D, E, F)
r	Steer age cohort under grazing system	(1, 2, ... , 9)
t	Year	(1, 2, ... , T)
$t_{(m)}$	Corresponding year to the counted month *m*	(1, 2, ... , T)

Table 5: List of decision variables.

Decision Variables		
Symbol	Description	Unit
	Baseline variables	
$LUC_{t,i,j}$	Land use change from *i* to *j* on year *t*	ha
$LU_{t,j}$	Area allocated to the land use *j* on year *t*	ha
$RPA_{t,p}$	Removed area from pasture *p* on year t	ha
EDA_t	Extra Deforested area for pasture	ha
$IS_{m,ks}$	Number of steers of age cohort *ks* inserted in the system at month *m*	head
$SS_{m,k}$	Number of stocked steers of age cohort *ks* at month *m*	head
WC_m	Number of weaned calves At month *m*	head
$PS_{m,ks}$	Number of purchased steers of age cohort *ks* at month *m*	head
$SSF_{m,k}$	Number of steers of age cohort *ks* selected to feedlot at month *m*	head

$IH_{m,kh}$	Number of heifers of age cohort *kh* inserted in the system at month *m*	head
$SH_{m,kh}$	Number of stocked heifers of age cohort *kh* at month *m*	head
$PH_{m,kh}$	Number of purchased heifers of age cohort kh at month *m*	head
SHB_m	Number of selected heifers for breeding at month *m*	head
$SCW_{m,kc}$	Number of stocked cows in breeding stage kc at month *m*	head
IC_m	Number of cows inserted in the system at month *m*	head
PC_m	Number of purchased cows at month *m*	head
$NBCx_m$	Number of newborn calves at month *m*	head
SCV_m	Number of stocked calves at month *m*	head
FSF_m	Number of steers finished under feedlot system at month *m*	head
$SFSy_m$	Number of stocked steers under feedlot system	head
TDM_m	Amount of dry matter transferred from month *m* to month *m+1*	kg
CIN_m	Cash inflows at month *m*	R$
COT_m	Cash outflows at month *m*	R$
UC	Used money from own capital	R$
$SCP_{m,c}$	Amount of crop *c* produced on month *m*	R$
CASHm	Cash at month *m*	R$
CINm	Cash income at month *m*	R$
COTm	Cash outcome at month *m*	R$
	Mitigation measures variables	
$CIRR_m$	Irrigation outcomes at month *m*	R$
CSC_m	Supplementation concentrate outcomes at month *m*	R$
CSP_m	Supplementation protein outcomes at month *m*	R$
FSC_m	Number of finished steers under concentrate supplementation at month *m*	head
ISC_m	Supplementation concentrate incomes at month *m*	R$
ISP_m	Supplementation protein incomes at month *m*	
$PFFC_m$	Pasture feed budgeting of supplement protein steers at month *m*	$Kg.head^{-1}$
$PFSC_m$	Pasture feed budgeting of supplement concentrate steers at month *m*	$Kg.head^{-1}$
PSC_t	Beef production from supplemented steers in year *t*	kg
PSC_t	Beef production from supplemented steers in year *t*	kg
$RFSC_{m,c}$	Ration feed budgeting of crop *c* of supplemented concentrate steers at month *m*	
$RFSP_{m,c}$	Ration feed budgeting of crop *c* of supplemented protein steers at month *m*	kg
SC_m	Number of steers supplemented with concentrate at month *m*	head
$SP_{m,kp}$	Number of steers of category *kp* supplemented with protein at month *m*	head
SSC_m	Number of steers selected for concentrate supplementation at month *m*	head

Table 6: List of parameters.

Symbol	Description	Value	Unit
	Baseline Coefficients		
$A_{t,lu}$	Farm total pasture area	Table 9	ha
ir	Interest rate discount	0.055	$\%.yr^{-1}$
$prr_{c,FL}$	Fraction of crop c in the feedlot ration composition	Table 11	dimensionless
α	Adjust parameter for animals selling price	0.37	dimensionless
γ_{CC}	Cull cow carcass yield	0.51	dimensionless
γFL	Feedlot steer carcass yield	0.51	dimensionless
γ_{H}	Heifer carcass yield	0.48	dimensionless
γ_{S}	Steer carcass yield	0.51	dimensionless
ζ	Ratio of herbage mass loss due to grazing	0.6	dimensionless
μ_{CV}	Mortality rate of calves	Table 1	$\%.mth^{-1}$
μ_{CW}	Mortality rate of cows	Table 1	$\%.mth^{-1}$
μ_{FL}	Mortality rate of feedlot steers	Table 1	$\%.mth^{-1}$
μ_{kh}	Mortality rate of heifers of age cohort *kh*	Table 1	$\%.mth^{-1}$
μ_{ks}	Mortality rate of steers of age cohort *ks*	Table 1	$\%.mth^{-1}$
$\sigma_{M(m)}$	Ratio of herbage mass loss due senescence	Table 10	dimensionless
ψ	Fraction of feedlot animals in relation of the total slaughtered animals	0.1	dimensionless
DA_{t}	Deforested area for pasture	Table 9	ha
BD_{t}	Beef demand on year t	0.5	Kg
ω_{CC}	Weight of cull cows	Table 1	kg
ω_{FL}	Weight of steers finished under feedlot	Table 1	kg
ω_{H}	Weight of heifers finished under pasture	Table 1	kg
ω_{kh}	Weight of heifers of age cohort *kh*	Table 1	kg
ω_{ks}	Weight of steers of age cohort *ks*	Table 1	kg
ω_{S}	Weight of steers finished under pasture	Table 1	kg
DM_{o}	Pasture productivity in t=1	4000	$kg.ha^{-1}$
$\tau_{M(m)}$	Minimum herbage mass (DM) transference at month *M(m)*	1000/2000[1]	$kg.ha^{-1}.mth^{-1}$
$prod_{p,M}$	Dry-matter productivity of pasture partition *p* on the calendar month *M*	Table 13	$kg.ha^{-1}.mth^{-1}$
dmi_{FL}	Dry-matter intake of feedlot males	Table 1	$Kg.head^{-1}.mth^{-1}$
dmi_{kh}	Dry-matter intake of heifers of age cohort *kh*	Table 1	$kg.mth^{-1}$
dmi_{ks}	Dry-matter intake of steers of age cohort *ks*	Table 1	$kg.mth^{-1}$

oc_{Max}	Available own capital	5E+10	$\text{R\$}$
$c_{i,j}$	Cost of land use/restoration cost	Table 2	$\text{R\$.ha-1}$
fc	Fixed costs per pasture area	13.3	$\text{R\$.ha}^{-1}\text{.mth}^{-1}$
c_{ins}	Cost of insemination	30.52	$\text{R\$.head}^{-1}$
nfc_{FL}	Non feed costs of feedlot finishing	22.5	$\text{R\$.head-1.mth-1}$
tc	Transaction cost of purchasing cattle	30	$\text{R\$.head}^{-1}$
mc_{FL}	Maintenance cost of cows of steers under feedlot	Table 1	$\text{R\$.head}^{-1}\text{.mth}^{-1}$
mch_{kh}	Maintenance cost of heifers of age cohort kh	Table 1	$\text{R\$.head}^{-1}\text{.mth}^{-1}$
mc_{kc}	Maintenance cost of cows of breeding starge kc	Table 1	$\text{R\$.head}^{-1}\text{.mth}^{-1}$
mcs_{ks}	Maintenance cost of steers of age cohort *ks*	Table 1	$\text{R\$.head}^{-1}\text{.mth}^{-1}$
prc_{kc}	Price of cows of breeding stage kc	Table 1	$\text{R\$.head}^{-1}\text{.mth}^{-1}$
pr_{FL}	Feedlot males selling price	Table 1	$\text{R\$.head}^{-1}\text{.mth}^{-1}$
prh_{kh}	Price of heifer of age cohort *kh*	Table 1	$\text{R\$.head}^{-1}\text{.mth}^{-1}$
prs_{ks}	Price of steers of age cohort *ks*	Table 1	$\text{R\$.head}^{-1}\text{.mth}^{-1}$
$prr_{salt,FL}$	Proportion of mineral salt in feedlot ration	1	%
	GHG emissions coefficients		
es_{ks}	Emissions factor of steers of age cohort ks	Table 1	$\text{Kg CO}_2\text{e.mth}^{-1}$
es_{kh}	Emissions factor of heifers of age cohort kh	Table 1	$\text{Kg CO}_2\text{e.mth}^{-1}$
ec_{kc}	Emissions factor of cows of age cohort kh	Table 1	$\text{Kg CO}_2\text{e.mth}^{-1}$
e_{CV}	Emissions factor of calves	Table 1	$\text{Kg CO}_2\text{e.mth}^{-1}$
e_{FL}	Emissions factor of feedlot steers	Table 1	$\text{Kg CO}_2\text{e.mth}^{-1}$
e_{SC}	Emissions factor of concentrate supplemented steers	Table 12	$\text{Kg CO}_2\text{e.mth}^{-1}$
e_{kp}	Emissions factor of protein supplemented steers of age cohort *kp*	Table 12	$\text{Kg CO}_2\text{e.mth}^{-1}$
	Supplementation concentrate coefficients		
c_{salt}	Cost of mineral salt	1.63	$\text{R\$.kg}^{-1}$
c_{urea}	Cost of mineral urea	1345	$\text{R\$.kg}^{-1}$
dmi_{SC}	DM intake of concentrate	Table 12	$\text{kg.head}^{-1}\text{.mth}^{-1}$
m_{SC}	Maintenance cost of supplemented concentrate steers	4.4	$\text{R\$.head}^{-1}\text{.mth}^{-1}$

nfc_{SC}	Non feed costs of supplementation concentrate	6.0	$R\$.head^{-1}.mth^{-1}$
$pdmi_{SC}$	Pasture DM intake of supplemented concentrate steers	Table 12	$R\$.kg^{-1}.mth^{-1}$
$prr_{c,SC}$	Proportion of crop c in the concentrate ration	Appendix A	%
$prr_{salt,SC}$	Proportion of mineral salt in concentrate ration	Appendix A	%
$prr_{Urea,SC}$	Proportion of urea in concentrate ration	Table 11	%
pr_{SC}	Selling price of steers finished under supplementation concentrate	Table 11	$R\$.head^{-1}$
γ_{SC}	Carcass yield of supplemented concentrate steers	0.51	dimensionless
μ_{SC}	Death rate of supplemented concentrate steers	0.0003	$\%.mth^{-1}$
ω_{CS}	Weight of finished steer under supplement concentrate	490	kg
Supplementation protein coefficients			
dmi_{SP}	DM intake of protein of steer of age cohort kp	Table 12	$kg.head^{-1}.mth^{-1}$
msp_{kp}	Maintenance cost of supplemented protein steer of age cohort *kp*	Table 12	$R\$.head^{-1}.mth^{-1}$
nfp	Non feed costs of supplementation protein	2.25	$R\$.head^{-1}.mth^{-1}$
$pdmi_{SP}$	Pasture DM intake of supplemented protein steers	Table 12	$kg.head^{-1}.mth^{-1}$
$prr_{c,SP}$	Proportion of crop c in the protein ration	Table 11	%
$prr_{NaCl,SP}$	Proportion of NaCl in protein ration	Table 11	%
$prr_{salt,SP}$	Proportion of mineral salt in protein ration	Table 11	%
$prr_{urea,SP}$	Proportion of urea in protein ration	Table 11	%
$pr_{SP,kp}$	Price of steer of age cohort kp supplemented with protein	Table 12	$R\$.head^{-1}$
$\mu_{SP,kp}$	Death rate of supplemented protein steers of age cohort kp	Table 12	$\%.mth^{-1}$
$\omega_{SP,kp}$	Weight of steer of age cohort kp under supplement protein	Table 12	kg
N inhibitors coefficients			
app_{Ninh}	N inhibitors application per appplied N	1.5	%
C_{Ninh}	Cost of N inhibitors	120	$R\$.kg^{-1}$
$cv_{N,N2O}$	Conversion factor of N into N2O	1	%
inNp	Nitrification inhibited proportion	0.5	%
Irrigation			
c_{IRR}	Cost of irrigation structure	23.6	$R\$.ha^{-1}.mth^{-1}$
$prodIR_{A,M}$	Pasture DM productivity of pasture A under irrigation	Table 14	$kg.ha^{-1}.mth^{-1}$
C stock model coefficients			
$c\omega_j$	C sequestration weight of land use j	Table 2	dimensionless
ε_j	C stock equilibrium of land use j	Table 2	$kg.ha^{-1}$

6.1 The model formulation

$$\max Cash_M \quad (1)$$

S.t:

Baseline equations

$$LU_{t,j} = A_{t,j} \ \forall j, t = 1 \qquad (2)$$

$$LU_{t,p} = LU_{t-1,p-\partial(t)} + \sum_{i} (LUC_{t,i,p} - LUC_{t-1,p-\partial(t),i}) - RPA_{t,p} \qquad (3)$$

$$t > 1$$

$$LU_{t,p} = LU_{t-1,p-\partial(t)} + \sum_{alu} (LUC_{t,i,p} - LUC_{t-1,p-\partial_D,i}) + DA_t + EDA_t - RPA_{t,p} \qquad (4)$$

$$t > 1,\ p = 3$$

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

$$\sum_{j} LUC_{t,p,j} + RPA_{t,p} \le LU_{t-1,p},\ t > 1 \qquad (6)$$

$$\sum_{j} LUC_{t,c,j} \le LU_{t-1,c},\ t > 1 \qquad (7)$$

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

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

$$IS_{m,ks} = 0.5W\mathrm{C}_m + PS_{m,k}s,\ \forall m, ks = 1 \qquad (10)$$

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

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

$$\begin{aligned} SH_{m,kh} = {} & IH_{m,kh} + (1-\mu_{kh})SH_{m-1,ks} + \sum_r \prod_{i=1}^{r} (1-\mu_{ks-i})^3 IH_{m-3r,ks-r} - \\ & - \sum_r \prod_{i=1}^{r} (1-\mu_{kh+1-i})^3 IH_{m-3r,kh-r+1} \;, \forall\; m\;, kh < 9\;, \quad r \in \{1,2,\ldots\} \end{aligned} \qquad (13)$$

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

$$IH_{m,kh} = 0.5W\mathrm{C}_m + PH_{m,kh} \;, \forall\; m, kh = 1 \qquad (15)$$

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

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

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

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

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

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

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

$$IC_m = PC_m + SHB_m \;, \forall\; m \qquad (23)$$

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

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

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

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

$$SSF_m = (1 - \mu_{FL})SSF_{m-1} + SSF_m - FSF_m \;, \forall\, m \quad (28)$$

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

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

$$SCP_{m,c} = SCP_{m-1,c} + prod_{c,M} LU_{t(m),c} - prr_{FL} dmi_{FL} SFS_m \quad , \forall\, c, \forall\, m \quad (31)$$

$$\tau_{M(m)} \sum_{p} LU_{t,p} - TDM_m \leq 0 \,, \quad \forall\, m \quad (32)$$

$$\sum_{p} prod_{p,M} LU_{t(m),p} \leq DM_0 \sum_{p} LU_{t(m),p} \quad (33)$$

$$\sum_{m \mid \frac{m}{12}=t} (\gamma_S \omega_S SS_{m,9} + \gamma_H \varpi_H SH_{m,9} + \gamma_{CC} \omega_{CC} SCW_{m,12} + \gamma_{FL} \omega_{FL} FSF_m) = BD_t \;, \forall\, t \quad (34)$$

$$CIN_m = prs_9 SS_{m,9} + \mathrm{prh}_9 SH_{m,9} + pr_{FL} FSF_m + prc_{12} SCW_{m,12} \,, \quad \forall\, m \quad (35)$$

$$\begin{aligned} COT_m = {} & fc * \sum_{p} LU_{t,p} + \sum_{ks=1}^{8} (tc + prs_{ks}) PS_{m,ks} + \sum_{kh=1}^{8} (tc + prh_{kh}) PH_{m,kh} + (tc + pr_C) PC_m + \\ & + \sum_{ks} mcs_{ks} SS_{m,ks} + \sum_{kh} mch_{kh} SH_{m,kh} + \sum_{kc} mc_{kc} SCW_{m,ks} + mc_{CV} SCV_m + \\ & + (nfc_{FL} + c_{salt} ppr_{salt,FL})(SSF_m + FSFf_m) + c_{ins} SHB_m + LI_m \sum_{i} \sum_{j} c_{i,j} LUC_{t(m),i,j} \quad , \forall\ m \end{aligned} \tag{36}$$

$$CASH_m = UC + CIN_m - COT_m \ , \ m = 1 \quad (37)$$

$$UC \le oc_{max} \quad (38)$$

$$CASH_m = CASH_{m-1} + CIN_m - COT_m \ , m > 1 \quad (39)$$

$$\begin{aligned} CASH_m = {} & CASH_{m-1} + CIN_m - COT_m - (1 + ir)^T UC + \\ & + \alpha \left(\sum_{ks=1}^{8} prs_{ks} SS_{m,ks} + \sum_{kh=1}^{8} prh_{kh} SH_{m,kh} + prc_{kc} \sum_{kc} SCW_{m,kc} \right) \quad (40) \\ m = {} & M \end{aligned}$$

Mitigation measures equations

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

$$FSC_m = (1 - \mu_{SC})^2 SSC_{m-2} \ , \forall\ m \quad (42)$$

$$PSC_t = \sum_{m \mid \left\lceil \frac{m}{12} \right\rceil = t} \gamma_{SC} \omega_{SC} FSC_m \ , \forall\ t \quad (43)$$

$$CSC_m = ((c_{urea} prr_{urea,SC} + c_{salt} prr_{salt,SC}) dmi_{SC} + nfc + msc) SC_m \ , \forall\ m \quad (44)$$

$$ISC_m = pr_{SC} FSC_m \ , \forall\ m \quad (45)$$

$$PFSC_m = (1 + \xi) pdmi_{SC} SC_m \ , \forall\ m \quad (46)$$

$$RFSC_{m,c} = prr_{c,SC} dmi_{SC} SC_m, \forall c, \forall m \quad (47)$$

$$SP_{m,kp} = (1-\mu_{SP}) SP_{m-1,kp} + SSP_m - (1-\mu_{SP})^3 SSP_{m-3,kp}, \; kp = 1, \forall m \quad (48)$$

$$SP_{m,kp} = (1-\mu_{SP}) SP_{m-1,kp} + (1-\mu_{SP})^{3(kp-1)} SSP_{m-3(kp-1)} - (1-\mu_{SP})^{3kp} SSP_{m-3kp}, \; kp > 1, \forall m \quad (49)$$

$$PSP_t = \sum_{m \mid \left\lceil \frac{m}{12} \right\rceil = t} \gamma_{SP} \omega_{SP} FSC_m \;, \forall t \quad (50)$$

$$CSP_m = (c_{urea} prr_{urea,SP} + c_{salt} prr_{salt,SP} + c_{NaCl} prr_{NaCl,SP}) \sum_{kp} dmi_{SP,kp} SP_{m,kp} + \\ + \sum_{kp} (nfp + msp_{kp} SP_{m,kp}), \forall m \quad (51)$$

$$PSP_t = \sum_{m \mid \left\lceil \frac{m}{12} \right\rceil = t} \gamma_{SP} \omega_{SP,kp} SC_{m,kp} \;, kp = 6, \forall t \quad (52)$$

$$ISP_m = pr_{SP} SP_{m,kp} \;, kp = 6, \forall m \quad (53)$$

$$PFSP_m = (1+\xi) \sum_{kp} pdmi_{SP} SP_{m,kp} \;, \forall m \quad (54)$$

$$RFSP_{m,c} = prr_{c,SP} \sum_{kp} dmi_{SP} SP_{m,kp}, \forall c, \forall m \quad (55)$$

$$CNIH_m = c_{NInh} \sum app_{Ninh,i,j} LUC_{t(m),i,j} \quad (56)$$

$$CIRR_m = c_{IR} LU_{t(m),A} \;, \forall m \quad (57)$$

All decision variables (Table 3) are non-negative.

The model can be explained in sections as follows. Any variable that represents number of animals is assumes continuous values. The reason is that the exact solutions are required to build the MACC, since the gross margin and liquid emissions of the baseline solution are compared with different solutions, when a mitigation measure is active in the model.
The size of the model, run for a 25 years period is 26769 variables per 24803 constraints.

6.2 The land use dynamics

In eq. **(1)**, the objective function, it is maximized the gross margin, which can be expressed as the cash at the last month, since the cash from a month *m* is transferred to month *m+1* without discounting.

Eq. **(2)** is responsible for allocating the initial land uses of the pastures types {A,B,C,D,E,F} and crops {Corn(silage), Corn(grain),Soybeans}.

In eq. **(3),** it is represented the pasture degradation and intervention – letting it naturally degrade, maintain in the same productivity level, or improvement, or even, changing the land use from pasture to crops (vice versa). As degradation was assumed to occurs biannually, the binary vector $\delta(t)$ is used as an index as follows:

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

The terms in the sum are the land flows across the different land uses, the third term, $LUC_{t,p}$ is used here to optimally remove lands from an use, since the available area for livestock production may decrease from one year to another.

Eq. **(4)** is similar to eq. **(3),** however, the land expansion, by deforestation, is automatically allocated in land use *p*=3, which represents pasture C. This equivalence was determined based on pasture DM productivity. Both DA_t and EDA_t represent deforestation, however the first one in an input, i.e, DA_t is different of zero when $LU_{t,p} > LU_{t-1,p.}$ The second, EDA_t is a decision variable. Its use is necessary to make the solution feasible in the case the total pasture area is not enough to accommodate production, or even if it is economically better to expand areas rather than intensifying the existing areas.

In eq. **(5)** it is expressed the crops land allocation. In this case, no degradation is applicable: every year they need to be planted and harvested, the land used for crops can come from any other crop or pasture.

Eq. **(6)** and **(7)** are used to limit the land use change variables according to the available area, the first for pastures and the second for crops.

6.3 Steers dynamics

In this section it is model the dynamics of the steers that were exclusively fed by pastures (without supplementation).

In eq. **(8)** it is modeled the steers transference throughout the time steps. The current number of steers in the system at time step *m* is given by the inserted animals, plus the transference from the *m-1*, first and second terms in the right-hand of the equation. The third term makes the transference from all the previous time steps. As the transference across the age cohorts occurs in three in three months, the model needs to bring to age cohort *ks* all the steers that were bought 3,6,9, … months ago, this is done by sum over the index *r*. The multiplicand is used to accumulate by age cohort transference; however, each age cohort is also a quarterly accumulation death rate. The last term, in the right hand side is analogous, but it accounts the steers that are being transferred from the age cohort *ks* at time step *m*, to the age cohort *ks+1* at *m+3*.

The eq. **(9)** accounts the number of finished steers, age cohort 9. In this cohort there is no transference of the same cohort, i.e, once steers becomes age cohort 9, it is slaughtered. Hence, the only term to make the transference across the time steps is the third term in eq. **(8)**.

Eq. **(10)** accounts the number of steers of the first age cohort inserted in the system. An animal can be inserted in the pasture system by: (i) purchasing then, or if (ii), a calf is born in the system. It was assumed half of the born animals are males, which will become weaned calves and then can be added to age cohort 1. The first term in the right-hand side represents (i), and the second, (ii).

Depending on the age cohort, what is associated with a weight (Table 1), steers can be selected to feedlot system (confinement). Theses selected amount of steers are given by the subtraction in Eq. **(11).**

Eq. **(12)** is modeled the insertion of the remaining age cohorts in the livestock system: they are inserted only by purchasing them. It can be seen in eq. **(18)** to **(22)** that cows are inserted only in the first breeding stage, afterwards, theses cows are transferred to the following stages.

6.4 Heifers dynamics

The heifers, as show I the diagram in Figure 1, heifers can be finished under grazing system similarly to what happens with the steers, or they can be selected to become cows, and thus, generate calves for the system.

Equations **(13)** to **(17)** are analogous to equations **(8)** to **(12)**, respectively, but for the heifers. Although, heifers cannot be moved to feedlot system – the heifers in the age cohort 7 can be selected to the breeding process, the subtraction term in eq. **(16)**.

6.5 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, the cows are discarded to be slaughtered (cull cows), and are used to meet the demand for beef.

Similarly to the steers and heifers dynamics, the number of cows in the system (stocked cows) is given by the transference of previous categories, in this case breeding stage across the time steps. The transfer is in function of the inserted cows variable ($IC_{m,kc}$).

In eq. **(18)** and **(19)**, it is accounted the number of cows in function of the breeding stage, *kc*. The number of cows in the breeding stage *kc*, at time step *m*, is given by the number of mf in *m-1*, subtracted the death rate, plus the cows that are changing from the other breeding stages to *kc*, at time step *m*. For instance, the number of the cows of *kc*=1, for any *m*, is given by the number of cows in m-1, plus the cows inserted in t, subtracted the number of cows that were inserted 9 months ago, respectively PC_m and IC_{m-9}, eq. **(18)**.

In the case of the last breeding stage, the cull cows, the number of cows at t is equal the number of cows that were inserted in the system 3 cycles ago, plus 9 months of pregnancy and 6 months of lactation, totalizing 69 months in the index of the variable in the right-hand side of eq. **(19)**.

Eq. **(20)** is the modeling of the cows which are in the pregnancy breeding stage *kc*, i.e for kc ϵ P = {1,4,7,10}, where P is the set of the cows in the pregnancy breeding stage. As an example, let *kc*=4, which represents the second pregnancy breeding stage. The amount of cows in this stage, is given by the number cows in *kc*=4 in *m*-1, plus the cows inserted in *m-18*, subtracted the number of cows inserted in the system 18 plus 9 (period of pregnancy) months ago, taking into account the accumulated mortality. The remaining pregnancy stages follow the same idea.

The eq. **(21)** and **(22)** are similar to eq. **(20)**, but they represent the number of cows in lactation, when *kc* ϵ L = {2,5,8,11}, and the number cows in non-lactation, when *kc* ϵ N = {3,9,6}

In eq. **(21)** is represented how the cows can be inserted in the system: by purchasing and/or selecting from heifers, notice SHB_m added in this equation, is removed from heifers of age cohort equal 7 (eq. **16**).

Eq. **(22)** gives the number of births in function of the inserted cows. At the time step t, the number of births will equivalent to the number of cows inserted in the system 9 months ago, plus the number of cows inserted 18 months ago (time of a complete cycle), and so forth, until it completes births per cows. It was assumed one cows generates one calf per cycle.
In eq. **(23)**, it is accounted the number of calves – not weaned – in the system. The amount of calves in time step *m* is given by the transference from *m-1*, plus the births in *m*, subtracted the births in *m*-6, sine the calves are breastfed during 6 months.

After 6 months, the calves are weaned, eq. **(24)**, and then, can are moved to the steers the age cohort 1, and heifers age cohort 1, eq. **(10)** and **(15)**, respectively.

6.6 Feedlot

In this section it is modeled the feedlot dynamics, in this model, only the steers can be confined.

In eq. **(27)**, it is accounted the number of finished steers under feedlot system – the steers finished under grazing system is described in eq. **(9)**. Once a steer is selected to feedlot, it takes two months to be slaughtered.

The amount of steers under feedlot (not finished yet), is given by the monthly transference, first term in the right-hand side, plus, the selected steers from grazing system, subtracted the finished steers, eq. **(28)**.

Eq. **(29)** is used to set the proportion of the total animals that are slaughtered under feedlot systems. As this proportion, ψ, is known as an annual average value, it is necessary sum in m the monthly finished animals to obtain the annual value. It done by summing in *m*, such that the ceil of the division of m by 12 is equal *t*, for all *t*.

6.7 Dry matter

In equation **(30)** it is written the feed budgeting of the grazing animals, consisting of steers, heifers, and cows. The parameter ξ, in the first term in the left-hand side of the inequality, is a ratio that represents the loss of DM by pressure of the grazing animals, the more animals, the lass DM losses. The term multiplying $(1+\xi)$ is the DM intake of all animals in the grazing system. The DM transference variable, TDM_m, represents the DM accumulated and not consumed at month *m*, however it will be available in the next month, discounted by a senescence loss, σ_M. In the right-hand side of eq. **(30)**, is represented the DM production, given by the sum of the individual productivity of the pastures types *p*.

The eq. **(31)** makes the stock of the crops production and feed budgeting of the confined steers. The amount of crop production *c* at month *m*, is given by the sum of the stock in *m-1*, plus the monthly production, which is proportional to the area allocated to the crop *c* on year *t(m)*, second term in the right-hand side, minus the amount of crop *c* used to make the ration for feeding the feedlot animals, last term in the equation.

Eq. **(32)** says that the grazing cattle cannot consume all the produced DM in a month m, instead, there is a minimum of DM per area that has to be transferred to the next month.

Eq. **(33)** is used to set the baseline DM productivity boundary. The productivity of the pastures, on any year $t > 1$, cannot be greater than the initial productivity. It was assumed that, in the baseline, the alternative to increase production will be deforestation rather than intensification, by pasture restoration.

6.8 Beef demand

Eq. **(34)** is the demand constraint. The model needs to meet the annual demand for beef. The beef total production is given by the terms inside the sum in left-hand side of the equation. The beef production of slaughtered steers under grazing system, for example, is given by the product of steer of age cohort 9, $SS_{m,9}$, by the yield carcass, by the finished animal weight, respectively, γ_{FL}, and ω_{FL}. The beef production from steers, cull cows and feedlot animals are analogous.

6.9 Cash flow

Eq. **(35)** represents the incomes of the system, which is given by sold of all the fished animals.

The outcomes, eq. **(36)**, are composed of the fixed costs per area, first term in the right-hand side, the cost of purchasing the animals, second to fourth term, the animal's maintenance costs, and the investments in pasture restoration and/or land use change costs, last term of the equation. The binary parameter vector, $L1_m$, is used here to set the discount in the first month of each year, otherwise as

$LUC_{t(m),i,j}$ is an annual variable, it would be discounted 12 months per year.

In the first month, besides the incomes and outcomes described above, there is a initial capital to be used, eq. **(37)**. The used capital is a decision variable in the model, eq. **(38)**.
In eq. **(39)** it is modeled the cash for the subsequent moths, in this case, the cash from m-1 is transferred to moth m, with zero discounts.

Eq. **(40)** represents the cash at the last month, which is equivalent to the gross margin, since the cash transference in made with zero discount rate. In the last month of production, the model has to pay the used capital *UC*, with a discount rate. The last term in the right-hand side, is the selling of the remaining animals in the system, i.e., the animals that achieved the slaughtered weight, in this case, to avoid distortions in the solution, a calibration parameter α is used, the parameter was determined such that the stocking rate kept approximately constant until the end of production.

6.10 Mitigation measures modeling

6.10.1 Pasture restoration:

This measure is already modeled in eq. **(3)**, **(4)** and **(6)**, however it is not fully optimized, since the pasture productivity is constrained by eq. **(33)**. Therefore, to access this measure mitigation potential and cost-effectiveness, it is necessary to disable eq. **(33)**.

6.10.2 Supplementation concentrate:

The eq. **(41)** to **(47)** are related to the supplementation concentrate measure.

In eq. **(41)** it is written the steers flux between the animals that are entering in the system, by the variable SSC_m, and the steers that are getting out of the system, FSC_m.

Eq. **(42)** is the finished steers, the supplementation takes two months.

Eq. **(43)** represents the beef production under supplementation concentrate, the two parameters multiplying $FSC_{m,}$ are the carcass yield and the steers finishing weight, which will give the monthly beef production.

Eq. **(44)** is the cost of the measure. it is given by the cost of the mineral urea and mineral salt contained in the ration (supplementation) formulation, summed up with non-feed and maintenance costs.

Eq. **(45)** is the cash income from the measure.

The steers supplemented with concentrate are also consuming DM from pastures, thus, eq. **(46)** represents the pasture feed budgeting of these animals. This equation is required to be added to eq. **(30)**, when this measure is evaluated.

The eq. **(47)** is the DM intake of crop c, the equation needs to be subtracted in right-hand side eq. **(31)**; the crop feed budgeting.

6.10.3 Supplementation protein:

In this measure modeling, it was created new categories, or age cohorts, of steers supplemented with protein. Once a steer is optimally selected to be moved from exclusive grazing system to this type of supplementation, by the variable SSP_m, the steer become a new category. Similarly to the grazing steers and heifers, an animal migrates from an age cohort to the next one, after 3 months. However, as the animals are being supplemented, the gain of weight is greater than the case with no supplementation, and the steers are finished earlier. Eq. **(48)** describes such dynamics for the first age cohort.

Eq. **(49)** is similar to **(48)**, however, is represents the dynamics of age cohort kp>1. It is important to notice that the number of animals is given in function of when the steers were added in the system, variable SSP_m.

Eq. **(50)** is the beef production of steers supplemented with protein.

Eq. **(51)** is analogous to eq. **(44)**, for concentrate; however, in this case, it is necessary to consider different costs per each age cohort.

Eq. **(52)** corresponds to the beef annual production of this measure.

Eq. **(53)** is cash incomes from this measure, given by the number of finished steers and the selling price.

The eq. **(54)** and **(55)** are similar to eq. **(46)** and **(47)**, but for the protein supplementation.

6.10.4 Feedlot Finishing:

This measure is already modeled in the baseline; however, it is constrained to 10% of total finished cattle, eq. **(29)**. To evaluate this measure, the adoption rate was “forced” to correspond to 20% of the total finished cattle.

6.10.5 Nitrogen Inhibitors:

Eq. **(56)** represents the cost of N inhibitors. It is given by the amount of N inhibitors applied, which is proportional to the N applied in the land use change interventions. As the land use change variable is an annual decision, the binary vector Lim is used to make the cash outflows only in one month of the year.

6.10.6 Pasture Irrigation:

This measure, eq. **(57)**, is modeled as a cost of irrigation – only in pasture A. The irrigation will lead to higher pasture DM productivity, i.e., instead use using $prod_{p,M}$, in Table 6, when irrigation is active in the model, it has to be considered $prodIR_{A,M}$, Table 6.

Chapter 7: Beef system emissions

7.1 Cattle emissions

The equations below are related to the cattle GHG emissions by enteric fermentation process. They based in emissions factors.

$$ce_m = \sum_{ks} es_{ks}SS_{m,ks} + \sum_{kh} eh_{kh}SH_{m,kh} + \sum_{ks} ec_{kc}SCW_{m,kc} + e_{CV}SCV_m + e_{FL}SFS_m \text{ , } \forall\ m \quad (58)$$

$$ce_{m,SC} = e_{SC}SC_m \text{ , } \forall\ m \quad (59)$$

$$ce_{m,SP} = \sum_{kp} e_{kp}SP_{m,kp} \text{ , } \forall\ m \quad (60)$$

Eq.**(57)** accounts the emissions of the cattle exclusively under grazing system. Each term in the right-hand side is composed by the emission factor, multiplied by the number of animals.

Eq. **(58)** and **(59)** account the emissions of steers supplemented with concentrate and protein, respectively.

7.2 Fertilization emissions

$$fe_m = 298cv_{N,N2O}\sum_{j}\sum_{j} app_{N,i,j}LUC_{t(m),i,j} \quad (61)$$

$$fe_{m,Ninh} = (1 - inNp)fe_m \quad (62)$$

Eq. **(61)** accounts the emissions from the application of fertilizers, based on N. The term inside the sum gives the amount of N applied of all land use change options. Part of this quantity is converted into N_2O, which is 298 times more potent that CO_2, in GWP.

The equation **(62)**, must replace eq. **(61)**, when the measure N inhibitors is going to be evaluated. In this case, part of the N will not be converted into N_2O.

7.3 Pasture emissions: the carbon stock modeling

The soil C stocks were calculated exogenously, the optimal solution calculated by LP model is used to estimate the C flux across the land transference when land use change occurs, and the stocks depending on the distance the current stock is from the equilibrium. The equilibrium values were obtained from simulations in the CENTURY model (Parton, 1987). The called "sequestration rate", is a calibration parameter that were obtained by making a least square adjustment of the developed C stock model with the CENTURY model (Table 2).

$$\begin{aligned}cs_{t,p} = {} & cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} LUC_{t,p} + \\ & + \Delta CS_{t,p} \ , \forall\ t,\ p \neq 3\end{aligned} \tag{63}$$

$$\begin{aligned}\Delta cs_{t,p} = {} & c\omega_p \left(\varepsilon_p - \left(cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \right.\right. \\ & \left.\left. - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} LUC_{t,p} \right)\right) LU_{t,p} \\ & \forall\ t,\ p \neq 3\end{aligned} \tag{64}$$

$$\begin{aligned}cs_{t,p} = {} & cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} LUC_{t,p} + \\ & + f\omega\left(EDA_t + DA_t\right) + \Delta cs_{t,p} \ , \forall\ t,\ p = 3\end{aligned} \tag{65}$$

$$\begin{aligned}\Delta cs_{t,p} = {} & c\omega_p \left(\varepsilon_p - \left(cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \right.\right. \\ & \left.\left. - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} LUC_{t,p} + f\omega\left(EDA_t + DA_t\right) \right)\right) LU_{t,p} \\ & \forall\ t,\ p = 3\end{aligned} \tag{66}$$

$$cs_{t,c} = \sum_i \frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,c} + c\omega_c \left(\varepsilon_c - \sum_i \frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,c} \right) LU_{t,c} \qquad (67)$$

$\forall\, t, \forall\, c$

In eq. **(63)** it is modeled the C stock per type of pasture. The first term in the right-hand side accounts transferred from pasture *p* to pasture *p*, if no degradation occurs (even years), or the transference from pasture *p-1* to pasture *p*, when degradation occurs (odd years). The first term inside the sum, represents the C flux from all the possible land uses that are converted to pasture *p* on year *t*. This transference is proportional the de C density on year *t-1*. The second term in the sum, is the C transferred from pasture *p* to any other land use. The term that is being subtracted represents the C removed from pasture *p* due to the loss of lands for pasture.

The sequestered C, eq. **(64)** on year *t* by pasture *p*, $\Delta cs_{t,p}$ depends on two factors: (i) the distance the current stock is from the equilibrium, and (ii) the called sequestration weight, $c\omega_p$ which is dependent of pasture species, climatic conditions, type and texture of the soil. (II) is calculated taking into account the C that is transferred to *p*, and removed from p, and then, use this value to measure the distance from the equilibrium value ε_p.

Eq. **(65)** and **(66)** are similar to **(63)** and **(64)**, however when *p*=3, it necessary to account the C transferred form forest soils due to deforestation.

In the case of the crops, eq. **(67)**, as crops have to be planted every year, the C transference among the land uses to crop c is simpler. It is necessary to account only the C transferred from the other crops and/or pasture to crop c, when land use change is done, and then, compare this value with the equilibrium.

It can be noticed from the C stock modeling that depending on the current C stock of each land use lu, and how the transference of C – by land use change – is done, the soils might emit or capture carbon, i.e., if the C moved form a set of land uses to a land use which the equilibrium is fewer than the transferred C, it will be C soil losses.

Chapter 8: Marginal Abatement Cost Curves

A MACC can be used to represents 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. Its essence is to identify the most economically efficient manner to achieve emissions reductions 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, 2009). In this work we opted for the latter, using detailed models are employed and the abatement potential and costs are individually modeled. The MACC can be presented in form of a histogram, where the C abatement potential lies on the x-axis, and the cost per ton of abatement in the y-axis.

In this work, we assessed the cost-effectiveness of six mitigation measures for livestock production, Table 3. The abatement potential of a measure *ms* (AP_{ms}), is calculated as the annual average of difference between the business as usual total GHG emissions (E_{BAU}) and the total emissions under the mitigation measure scenario (E_{ms}) during the production period T:

$$AP_{ms} = \frac{E_{BAU} - E_{ms}}{T} \quad (68)$$

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

$$CE_{ms} = \frac{GM_{BAU} - GM_{ms}}{AP_{ms}} \quad (69)$$

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

As observed in eq. **(67)** and eq. **(68)**, AP_{ms} and CE_{ms} are average values. There are annual variations on beef demand, which will lead to changes in pasture productivity and C soil stocks. For instance, restoring grasslands in one year will have its real effect on C stocks in subsequent years. If a pasture in

C equilibrium has a variation over DM productivity, it will take about 20 years until it come into equilibrium again (IPCC, 2010). In this sense the MACC is by definition, represents average values.

Chapter 9: Results and Discussion

9.1 Baseline Emissions

The largest share of GHG emissions in *Cerrado* 78Mt CO2e.yr^{-1} comes from enteric fermentation process. Deforestation accounts for 25MtCO$_2$e.yr^{-1}.

The model shows that the degradation process is also a potential source of emissions, accounting for 4.35MtCO$_2$e.yr^{-1}. The total average emissions are 111.85 MtCO2e.yr^{-1}, or 2.4GtCO$_2$e, from 2010 to 2030. As forecast beef demand is increasing, total emissions to 2020 are expected to be about 122.44MtCO$_2$e, and reaching 142.8MtCO$_2$e in 2030, where 48.7Mt are due to deforestation.

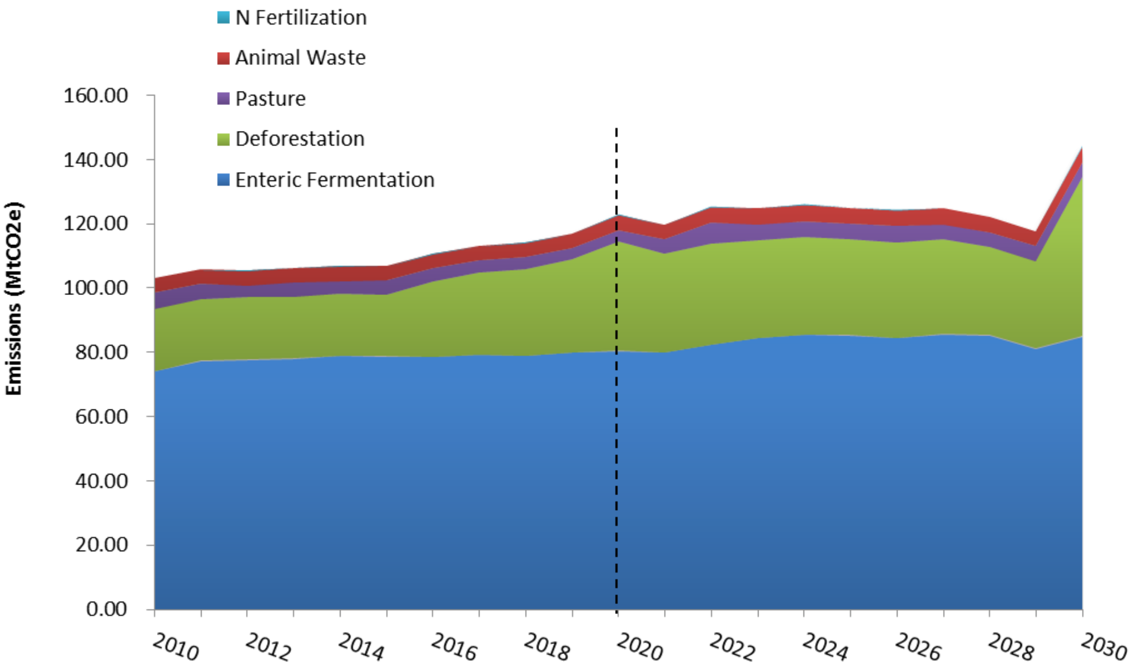

Figure 3: Cerrado baseline annual emissions from 2010 to 2030.

The baseline productivity constraint implied in an average deforestation rate of 173 10^{3}ha.yr^{-1} for the *Cerrado* region.

This is equivalent to the minimum deforested area required by beef production if no investments in intensification are taken over the analyzed period. Emissions attributed to the use of fertilizers were not significant, it accounted only for an average of 0.2MtCO_2e.yr-1. This was expected, since not all types of restoration require the application of N.

9.2 Marginal abatement cost curves for Cerrado

Three of the five mitigation measures simulated (concentrate supplementation, protein supplementation, and pasture restoration) are negative cost: R$-15.65/kt$CO_2e, R-5.64/ktCO_2e and R$-0.12/kt$CO_2$e^{-1}, respectively. Due to the large area of ~60Mha of the *Cerrado*, and summing with the low productivity of 10t of DM.ha-1.yr-1, pasture restoration is the most widely applicable mitigation measure, with cost effectiveness close to zero: R$-0.12/kt$CO_2$e. Boosting C soil sequestration may avoid 503MtCO_2e from 2010 to 2030. The Abatement Potential for this measure is 23.4MtCO_2e.yr^{-1}. Pasture restoration AP is composed of two abatement components: C sequestration and avoided deforestation. Approximately 95% of this reduction is due to the latter, and the remaining 5% due pasture C sequestration. This proportion reflects the current poor average productivity of *Cerrado*. Furthermore, the results suggest only limited intensification potential is possible until 2030, in the baseline scenario. The baseline pasture productivity average for the region is about 10t-DM.ha^{-1}.yr^{-1}, whereas without the productivity constraint, it increases to 11.2t-DM/ha.yr^{-1} and the corresponding average of C sequestration rate of 0.32Mg.ha^{-1}.yr^{-1}. However, Cerri et. Al (2003) showed C sequestration rates of 10Mg.ha.yr^{-1} can be achieved in intensive pasture production farms. In the baseline, there was no C capture into the soil. Pastures were actually emitting 0.06 tCO_2e.ha^{-1}.yr^{-1}, caused by degradation processes, land use change (from pasture to soya and or corn) and alteration of C stocks by deforestation.

The AP of confinement is 470ktCO_2e.yr^{-1}, but costs are high: R$61.17/t$CO_2$e. Nitrification inhibitors are the least effective measure for *Cerrado* livestock production, mainly due to the small amount of N applied for pasture restoration and high cost of the product in Brazil.

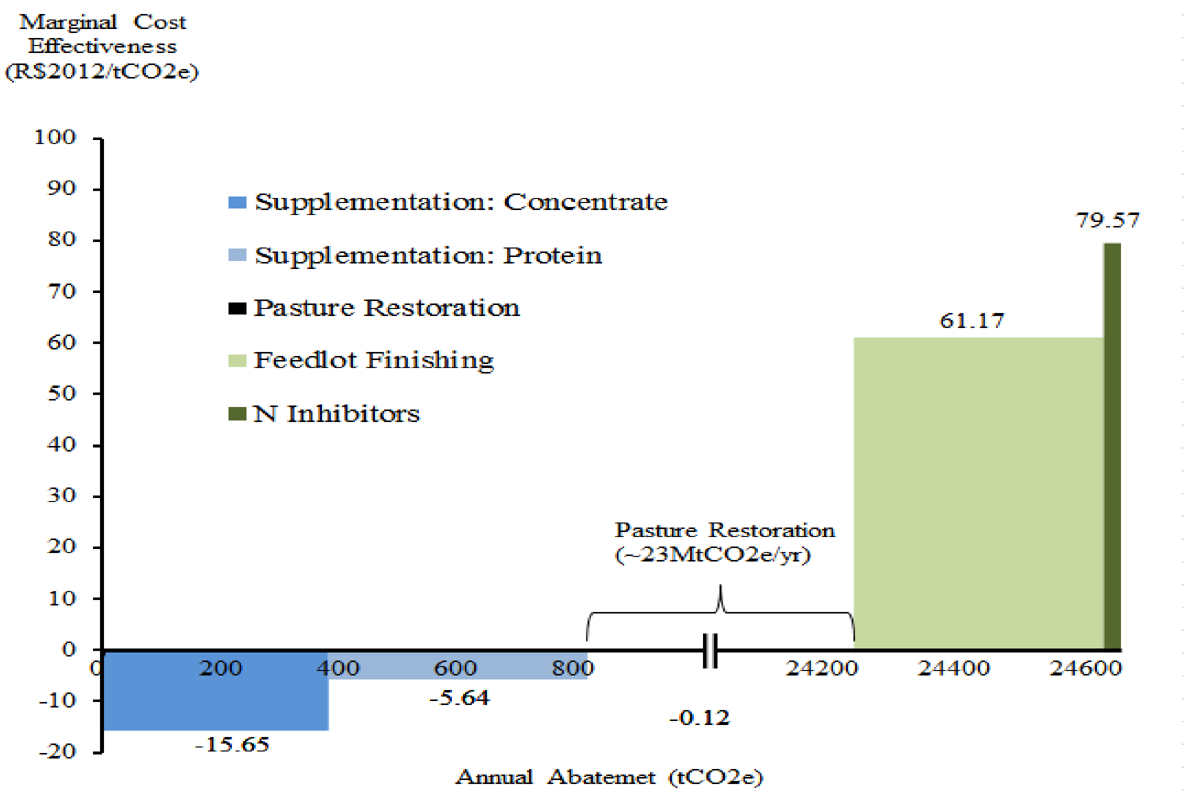

Figure 4: Marginal abatement cost curve: mitigation measures for Cerrado livestock production (over what time period).

As shown in Table 3, the mitigation measures are optimized (except, feedlot and N inhibitors). The adoption rate associated with the constructed MACC was:

Table 7: Mitigation measures adoption rate.

Mitigation Measure	Adoption rate	Unit
Supplementation: Concentrate	12	%
Supplementation: Protein	2.2	%
Pasture Restoration	314.7	10^3 ha.yr^{-1}
Feedlot Finishing	15	%
N Inhibitors		10^3 ha.yr^{-1}
Pasture Irrigation	0	10^3 ha.yr^{-1}

The feedlot, protein and concentrate adoption rate is calculated as the percentage of the total finished animals.

The results showed pasture irrigation is not a mitigation measure under the constructed scenario. Irrigation drove to higher emissions when compared with the baseline.

9.3 Pasture restoration sensitivity analysis: demand versus emissions

C stocks are highly dependent on pasture productivity. It is evident that there is a strong relationship between pasture restoration and beef demand. The object of the analysis was to evaluate the effects on pasture restoration potential and cost effectiveness in function of variations over the projected demand.

The question is what would be the effects on the abatement potential and cost effectiveness of pasture restoration, as a mitigation measure, if the demand forecast, used as an input in the model, decrease by -30%, -20%,-10%? or if demand increases by 10%, 20%, or 30%?

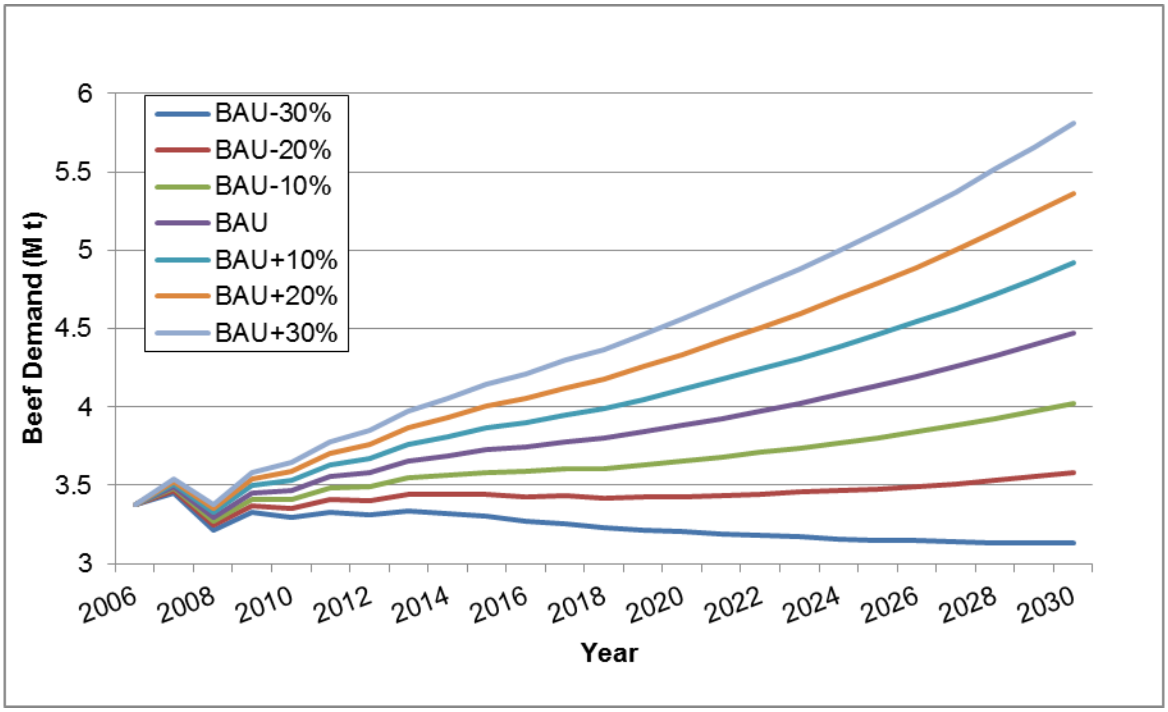

Figure 5: Beef Demand forecast for the Cerrado region (BAU) and its variations from -30% to 30%.

Using the demand projections, pasture restoration AP and CE was evaluated for each of the demand variation and then compared with the AP and CE of the BAU demand. The results are: if demand projection rises by 10% (D+10%, in Figure 5), the AP increases by 6% and CE falls to R$-1.45/ktCO$_2$.

For a +30% variation in demand, AP increases by 16%, and CE falls to R$-2.53/ktCO$_2$e. Further results are present in the figure bellow:

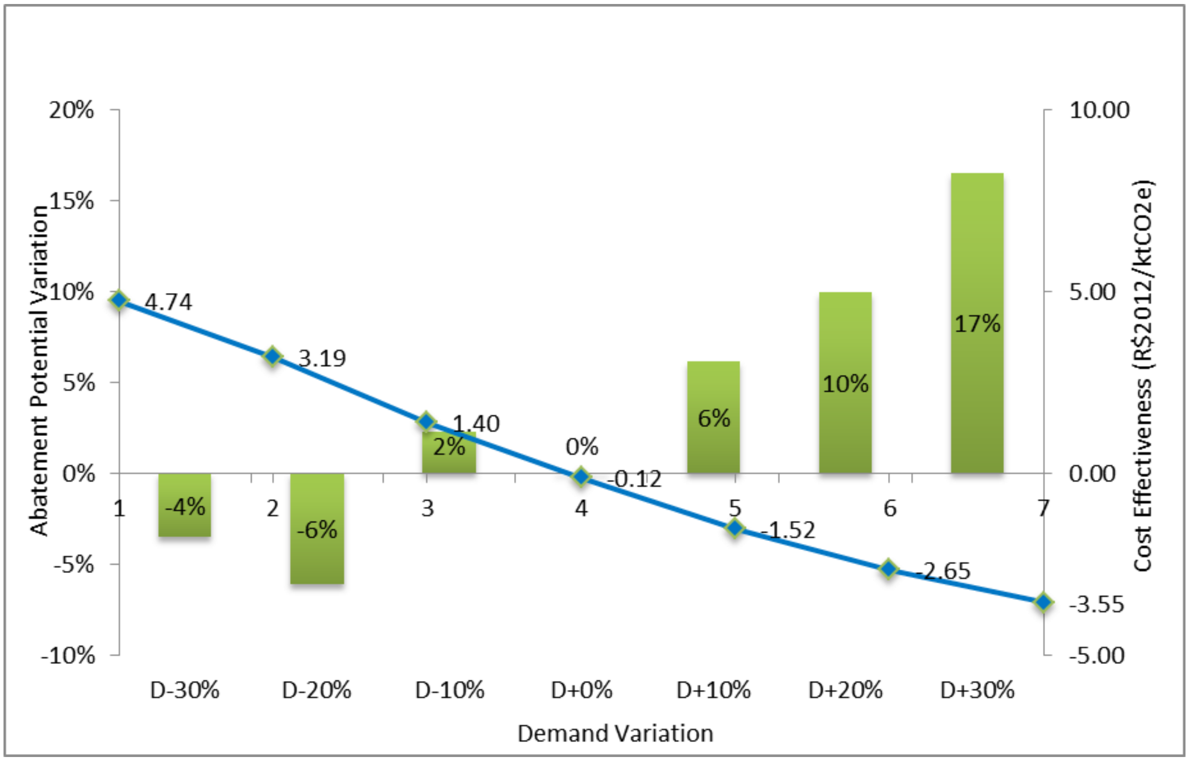

Figure 6: Pasture restoration AP and CE sensitivity analysis.

If demand decrease by -10%, pasture restoration still can be used as a mitigation measure, since the abatement potential increases by 2%, however the cost effectiveness jumps from R$-0.1/ktCO$_2$e to R$1.34/kt CO$_2$e. Nevertheless, it is much less efficient in terms of GHG mitigation rather than increasing demand by 10% - in this situation, the AP increases by 6%, while CE decreases to the negative value of R$-1.45/ ktCO$_2$e.

On the other hand, if beef demand decreases by -20%, or -30%, it will make pasture restoration inapplicable, in the sense that there will not be sufficient production to boost or even keep the C stocks by pasture soils. Under the demand reduction of -20% and -3-%, the AP for pasture restoration decreases by -6% and -3%, respectively, in relation to the AP for the BAU demand (Figure 5).

In the same analysis, but accounting the total liquid emissions by demand variation, the results showed lower emissions when demand increases and higher emissions if demand decreases. If demand decreases by -30%, -20% or -10%, the emissions increase by 5%, 4% and 1%, respectively. On the other hand, when demand increases by 10%, 20% or 30%, the total liquid emissions decrease by -2%, -3% and -4%, respectively.

Chapter 11: Conclusion

Pasture restoration is the most promising mitigation measure, in terms of abatement potential volume. It responds for an AP of 23.4Mt.yr^{-1}, it is more than 17 times the AP of all the others measures put together. It is important to notice that the difference between the baseline and the pasture restoration scenario is that in the first one it was assumed constant forage productivity - which implied the model needs to open new areas to increase production. In the pasture restoration scenario, the model was also allowed to open new lands with zero cost. Nevertheless, no extra deforestation occurred. This fact indicates that it is economically better to increase production by restoring degraded lands rather than expanding the area, since the area expanded can not be withdraw from the system, by will degrade and generate restoration costs.

The measures with the biggest cost effectiveness are dietary supplementation; these measures work because they are used to balance the loss of DM production during the dry months. The *Cerrado* biome is predominantly seasonal tropical, meaning dry winters and rainy summers. Dry months, range from June to August, and pasture productivity falls and supplements are needed as an alternative. If Nellore are supplemented they can finished earlier, thereby reducing emissions.

The pasture restoration sensitivity analysis showed that decreasing beef consumption by more than 10% will not decrease emissions, it might actually make it grows due to the loss of C stocks by de stocking. Increasing beef demand tends to linearly increases pasture restoration abatement potential, due to the increasing of C soil stocks. Despite the growth of NH_4 emissions by an increased production, the C sequestration potential is enough to compensate the emissions, so that the value of total emissions is lower.

The biggest source of emissions from the *Cerrado* is by far the enteric fermentation process, responsible for about 70% of its annual emissions. The second largest source comes from deforestation. The baseline is essentially defined by constraining pasture productivity to be constant during all the period: ~10kg-DM.ha^{-1}.yr^{-1}. In this case, there will be pressure for a deforestation rate of 181.85 10^{3}ha^{-1}.yr^{-1}, so that *Cerrado* can meet the net demand predictions. Furthermore, with the productivity constraint, i.e., without intensification in the region, the model indicates a loss of 8.35Mt CO_2e.yr^{-1} of the C soil pools, by degradation process.

Chapter 11: Conclusion

The results show that the animals direct emissions can be offset by the large potential of carbon sequestration in the Cerrado pasture soils, at least in the short time.

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Appendix

Table 8: Breeding stage index for the cow-calf operation dynamics.

Breeding stage (*kc*)	Description
1	1st pregnancy
2	1st lactation
3	1st non-lactation
4	2nd pregnancy
5	2nd lactation
6	2nd non-lactation
7	3rd pregnancy
8	3rd lactation
9	3rd non-lactation
10	4th pregnancy
11	4th lactation
12	4th non-lactation (cull cow)

Table 9: Cerrado pasture area projections (34%) of total Brazil pasture area projections form the Low Carbon case study (Gouvello 2011).

Year	Area (ha)	Deforested area (ha)
2006	71022223	0
2007	70149667	0
2008	69829414	0
2009	69450188	0
2010	69263545	0
2011	69105636	0
2012	69063027	0
2013	68980468	0
2014	68872624	0
2015	68852662	0
2016	68890613	37951
2017	68949712	59099
2018	69021091	71380
2019	69110828	89736
2020	69249874	139046
2021	69356158	106284
2022	69470469	114311
2023	69574231	103761
2024	69677183	102952
2025	69775300	98117
2026	69872213	96914
2027	69967590	95377
2028	70042081	74491
2029	70116497	74416
2030	70400244	283747

Table 10: *Senescence loss of pasture DM production.*

Month	Senescence (Dimensionless)
Jan	0.38388
Feb	0.40992
Mar	0.32802
Apr	0.21462
May	0.14028
Jun	0.06384
Jul	0.03906
Aug	0.04746
Set	0.11466
Oct	0.31164
Nov	0.28266
Dec	0.41076

Table 11: rations formulations.

Crop	Ration Formulation (%)		
	Feedlot	Concentrate	Protein
Corn(grain)	83	80	15
Corn(Silage)	11	0	0
Soybeans	5	17	39
Urea	0	2	12
Mineral Salt	1	1	19
NaCl	0	0	15

Table 12: Supplemented steers(age cohort), DM intake, weight, and emissions factors (IPCC, Tier 2)

Age cohort	Age, months	Death rate (%.mth-1)	Avg SBW, kg	Weight Gain (kg.day-1)	DMI, kg/day (supplement)	DMI, kg/day (Pasture)	CO_2, kg.-head.-1.mth-1	Price (R\$2012.head^{-1})	Maintenance Cost (R\$2012.head^{-1})
Contentrate supplementation									
SC	[27,32]	0.03	457	1.0	3.0	12.941	132.7877	1635	4.4
SP	Protein supplementation								
1	[6,9)	0.42	207	0.61	0.33	5.9	60.15	660	2.43
2	[9,12)	0.2	266	0.63	0.33	7.2	73.74	850	2.72
3	[12,15)	0.2	331	0.76	0.00	9.2	94.10	1100	3.29
4	[15,18)	0.03	397	0.68	0.00	9.9	101.05	1300	3.86
5	[18,21)	0.03	451	0.47	0.64	8.9	91.83	1520	4.43
6	[21,24)	0.03	481	0.38	0.77	8.4	87.41	1620	4.74

Table 13: Dry matter productivity per land use type and month.

Month	Land use DM productivity (kg.ha^{-1}.mth^{-1})								
	A	B	C	D	E	F	Corn(grain)	Corn(Silage)	Soybeans
Jan	2742	2388	1653	1143	762	507	0	0	0
Feb	2928	2532	1737	1203	801	534	0	9040	2490
Mar	2343	1998	1344	930	621	414	3840	0	0
Apr	1533	1533	1245	861	573	384	0	0	0
May	1002	1002	813	564	375	249	0	0	0
Jun	456	456	369	255	171	114	0	0	0
Jul	279	279	228	156	105	69	0	0	0
Aug	339	339	276	189	126	84	0	0	0
Set	819	819	666	462	306	204	0	0	0
Oct	2226	1917	1305	903	603	402	0	0	0
Nov	2019	1746	1197	828	552	369	0	0	0
Dec	2934	2574	1803	1248	831	555	0	0	0

Table 14: Pasture A productivity under irrigation.

Month	Land use DM productivity ($kg.ha^{-1}.mth^{-1}$)
	Pasture A
Jan	2742
Feb	2928
Mar	2343
Apr	1533
May	1002
Jun	456
Jul	279
Aug	339
Set	819
Oct	2226
Nov	2019
Dec	2934