EVANDRO LIMA DA SILVEIRA BATISTA

MODELING THE ECONOMIC AND ENVIRONMENTAL IMPACTS OF CATTLE RANCHING INTENSIFICATION IN MATO GROSSO

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Meteorologia Aplicada, para obtenção do título de *Doctor Scientiae.*

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BIOGRAFIA

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ABSTRACT

BATISTA, Evandro Lima da Silveira, D.Sc., Universidade Federal de Viçosa, December, 2016. **Modeling the economic and environmental impacts of cattle ranching intensification in Mato Grosso.** Adviser: Britaldo Silveira Soares Filho. Co-Advisers: Fabiano Alvim Barbosa and Aristides Ribeiro.

Cattle ranching occupy more land than any other production activity in Brazil and accounts for 44% of greenhouse gas (GHG) emissions from the land use sector. In response, Brazil has proposed a large-scale pasture restoration target as a mitigation measure for its Nationally Determined Contribution (NDC). Pasture restoration is, however, only one option in a portfolio of investments that could be brought to bear to encourage intensification in beef production. To analyze the potential impacts, i.e. economic and overall GHG emissions, from mixes of intensification strategies—from pasture restoration to improved health and reproductive management, pasture supplementation, and feedlot operations—, we developed a simulation model of the cattle ranching system (SimPec) and applied it to Mato Grosso state. Our results show that large-scale pasture restoration, instead of reducing GHG emissions, threatens the success of Brazil's NDC. Soil carbon fixation after pasture restoration does not compensate marginal emissions due to higher stock densities; simply increasing beef production will lead to an overall rise in GHG emissions from the cattle sector. Rather than pasture restoration, investments in confinement operations along with complementary improvements in production strategies are more likely to prompt better economic, productive, and, in particular, environmental outlooks for the cattle sector in Brazil.

RESUMO

BATISTA, Evandro Lima da Silveira, D.Sc., Universidade Federal de Viçosa, dezembro de 2016. **Modelagem dos impactos econômicos e ambientais da intensificação da bovinocultura de corte no Mato Grosso.** Orientador: Britaldo Silveira Soares Filho. Coorientadores: Fabiano Alvim Barbosa e Aristides Ribeiro.

A bovinocultura de corte ocupa mais terra que qualquer outra atividade produtiva no Brasil e é responsável por 44% das emissões de gases de efeito estufa (GHG) pelo setor de uso e mudança de uso do solo. Em resposta, o Brasil tem proposto a restauração de pastagens em larga escala como uma iniciativa para sua Contribuição Nacionalmente Determinada (NDC). A restauração das pastagens é, contudo, apenas uma das alternativas de investimento que poderiam encorajar a intensificação da produção de carne bovina. Para analisar os impactos potenciais, i.e. na economia e nas emissões totais de GHG, de diferentes arranjos de estratégias de intensificação – desde a restauração das pastagens à melhorias no manejo reprodutivo e sanitário, suplementação alimentar e terminação em confinamento – nós desenvolvemos um modelo de simulação de sistemas de produção de bovinos de corte (SimPec) e realizamos um estudo para o estado do Mato Grosso. Nossos resultados indicam que a restauração das pastagens em larga escala, ao invés de reduzir as emissões de GHG, pode ameaçar o sucesso da NDC brasileira. A fixação de carbono no solo após a restauração das pastagens não compensa as emissões marginais por conta das altas densidades de lotação animal. Apenas aumentar a produção de carne bovina levará a um aumento nas emissões totais da pecuária de corte bovina. Ao invés da restauração massiva das pastagens, investimentos em suplementação alimentar dos animais a pasto e o confinamento juntamente com melhorias complementares nas estratégias de produção são mais prováveis de impulsionar melhorias econômicas, produtivas, e, em particular, perspectivas ambientais para a bovinocultura de corte no Brasil.

1 Introduction

Global demand for food, fiber and biofuels is growing rapidly and will require a substantial increase in agriculture production in a near future (Tilman *et al.*, 2011; Alexandratos e Bruinsma, 2012). The current world cropland yield gap reveals the potential owned by some areas to raise their agricultural outputs and hence assist stronger to achieving future food security (Neumann *et al.*, 2010).

In the tropics, where much of these areas are located, most of the increase in agricultural production has coming from agricultural land expansion in natural ecosystems (Gibbs *et al.*, 2010). However, as climate change means a threat to their agricultural productivity (Berg *et al.*, 2013; Pires *et al.*, 2016), urge the necessity to mitigate greenhouse gas (GHG) emissions, which will demand a more sustainable path for agricultural expansion (Tilman *et al.*, 2011).

Brazil, one of the major world agricultural powerhouse, can play an essential role in this aim. The country can support much of the future world demand since it can both expand their croplands and improve their yields (Ray *et al.*, 2013). In addition, holds the greatest tropical forest, which plays an impressive contribution on global climate regulation by the huge amount of carbon that stocks (Saatchi *et al.*, 2011). These unmatched conditions can ensure to Brazil the position of first major developing country to balance development with conservation.

With a 67 percent decline in deforestation from the historical baseline and an associated reduction of 2 billion tons of CO_2 emissions (Seeg, 2016), Brazil has recently demonstrated its potential to evade this outcome. Notwithstanding, more than half of Brazilian GHG emissions still comes from LULUCF (Land Use, Land Use Change and Forestry) (Seeg, 2016) and conflicting development and conservation policies, as well as increased demands for agricultural products from Brazil, threaten the permanence of this success (Laurance *et al.*, 2005). Thus, to reduce GHG emissions, as proposed by Brazilian government in Copenhagen and later enlarged in Paris (Brasil, 2009; 2015), will demand a national strategy that supports the agricultural expansion while reduces intensity emissions of agricultural products and avoid new deforestation.

The cattle ranching industry is faced as a key component of any policy that seeks reconcile rural development with conservation in Brazilian territory. The activity appropriates more land than any other in Brazil. Approximately 220±20 million hectares are in pastureland (70% of all agricultural land) of which 70 million are in the Amazon region (Soares-Filho *et al.*, 2014), where a sharp herd growth is underway (Barbosa *et al.*, 2015) despite low economic returns (Bowman *et al.*, 2012). Even with a set of incentives that affect Amazon deforestation (Laurance *et al.*, 2005), cattle ranching is pointed as the major responsible since it is closely associated with new deforestation (Soares-Filho *et al.*, 2010). Of particular importance, Brazil's cattle herd of about 215 million head (Ibge, 2016) accounts for 74% of agricultural GHG emissions (Seeg, 2016), which amounts to 44% of GHG emissions from the land use sector and this figure keeps increasing as Brazil further reduces deforestation rates in the Amazon (Inpe, 2016) and demand for beef rises nationally and internationally (Tilman *et al.*, 2011; Mapa, 2016b).

Despite being the world second largest beef producer and beef exporter (Imea, 2016b; Usda, 2016b), there are only a few producers advancing the economic and productive potential of cattle ranching (Barbosa *et al.*, 2014). Brazil's beef industry continues to be dominated by lower productivity and lower value of production than those of its main competitors (Anualpec, 2015; Mapa, 2016a; Usda, 2016a). While Brazil produced 9.2 million tons of beef (Mapa, 2016a) from a herd of 215 million head in 2015 (Ibge, 2016), with a gross product value of US$ 22 billion (Mapa, 2016a), the USA produced 10.8 million tons of beef from a herd of 89 million and generated a product value of US$ 105 billion (Usda, 2016a).

Recently, intensification of cattle ranching has been suggested as a low cost option to both mitigate GHG emissions and increase profits to ranchers in Brazil (De Gouvelo *et al.*, 2010; Strassburg *et al.*, 2014; De Oliveira Silva *et al.*, 2016). In addition to meeting rising demand for beef (Mapa, 2016b), cattle intensification is proposed as means to reduce pressure on forests, thereby sparing land for agriculture expansion and supporting conservation outcomes (Bustamante *et al.*, 2012; Strassburg *et al.*, 2014). More intensive systems also may reduce GHG emissions per unit of beef produced by shortening steers' average lifetime compared with extensive systems (Cardoso *et al.*, 2016).

Land rent theory, however, alerts for the risk of more land conversion due to intensification (Angelsen, 2010) as these type of systems demand large-scale of production (Goulart *et al.*, 2016). Regardless, ranchers in Brazil now face new environmental and economic conditions and there is a growing concern in civil society, the productive sector and government, about negative environmental impacts from cattle ranching with respect to the use of large tracts of land, hence association with deforestation, inefficiency of natural resource use, and GHG emissions (Tilman *et al.*, 2001; Steinfeld *et al.*, 2006; Bustamante *et al.*, 2012; Sattari *et al.*, 2016).

In this light, Brazil has proposed to carry out a large-scale pasture restoration as one of the cornerstone mitigation measure of its Nationally Determined Contribution (NDC) to the Paris agreement (Brasil, 2015). This target includes the restoration of 15 Mha of pastures by 2030 in additional to 15 Mha already proposed by Brazil's ABC (Low Carbon Agriculture Plan) (Plano Abc, 2012). Importantly, this goal relies on the assumption that pasture restoration holds a potential to sequester carbon in the soil (Lal *et al.*, 2006; Maia *et al.*, 2009; Braz *et al.*, 2013), while improving roughage digestibility, thereby reducing enteric methane emissions (Thornton e Herrero, 2010; Gerber *et al.*, 2013).

Pasture restoration is, however, only one option of a portfolio of investments aimed at intensification. Alternative or complementary measures include, among others, supplemental feeding, feedlot operations, and improvement in health and reproductive management, *i.e.* enhanced genetics and fertility rates (Thornton e Herrero, 2010; Barbosa *et al.*, 2015). Previous studies have analyzed cattle ranching intensification with respect to individual productive, economic or environmental choices separately (Barbosa *et al.*, 2014; Strassburg *et al.*, 2014; Cardoso *et al.*, 2016; De Oliveira Silva *et al.*, 2016), but the effect of a mix of strategies on the economics and environmental outcome of cattle intensification remains unclear. One particular challenge is to determine the right dose of strategies that could meet future demands for beef, meanwhile lowering GHG emissions as well as other environmental impacts in a plausible scenario of increasing economic competition within the cattle sector and from other meats. This analysis must also take into account that adoption of available technologies and strategies that may vary across space, time, and landowner characteristics (Gil *et al.*, 2015). Details such as climate and terrain aptitude, property size, local infrastructure, distance to markets, input, and output prices will define if and where intensification modes will succeed (Bowman *et al.*, 2012; Gil *et al.*, 2015).

To evaluate the possible outcomes of Brazil's policy targets of beef production and pasture restoration (Plano Abc, 2012; Brasil, 2015; Mapa, 2016b), we developed a simulation model (SimPec) that integrates in a systemic way the impacts of a mix of intensification strategies on the productivity and economics of the system along with resulting GHG emissions. We then applied this model to Mato Grosso, as a case study.

2 Methods

2.1 General approach

The dynamics of cattle ranching, in a complete cycle of beef production, were simulated by SimPec model at a municipality spatial unit. Although partial cycle systems— where individuals specialize on one component of the cycle— are also common, the interaction between these systems on a regional basis, such as a whole municipality, can be pictured as a single cycle. SimPec calculates the costs and investments for improving pasture yields and management, herd health and fertility, supplementary feeding, and steer finishing in feedlot and in pasture with supplementation required to attain a pre-determined series of productive indices. Each modeled management scenario consists thus of specific doses of these investments, in other words, of a mix of intensification strategies. The model then assesses the impact of a management scenario on herd growth and age distribution, beef volume and productivity, net revenues, and associated GHG emissions. For each municipality, the model simulates, monthly from 2012 to 2030, the dynamics of a representative ranching system for the region taking into account the municipality's initial 2012 herd size (Ibge, 2016) and structure—*i.e.*, weight, gender and age distribution (Anualpec, 2015)—, pasture area (Soares-Filho *et al.*, 2016), and property size distribution (Ibge, 2016). For the intensification potential, the model also considers the regional logistics and agricultural aptitude (Barbosa *et al.*, 2015) along with additional underlying scenarios of land use change (Soares-Filho *et al.*, 2016) (Figure 1). Data base used in this study and their respective sources and assumptions are described in Table 1.

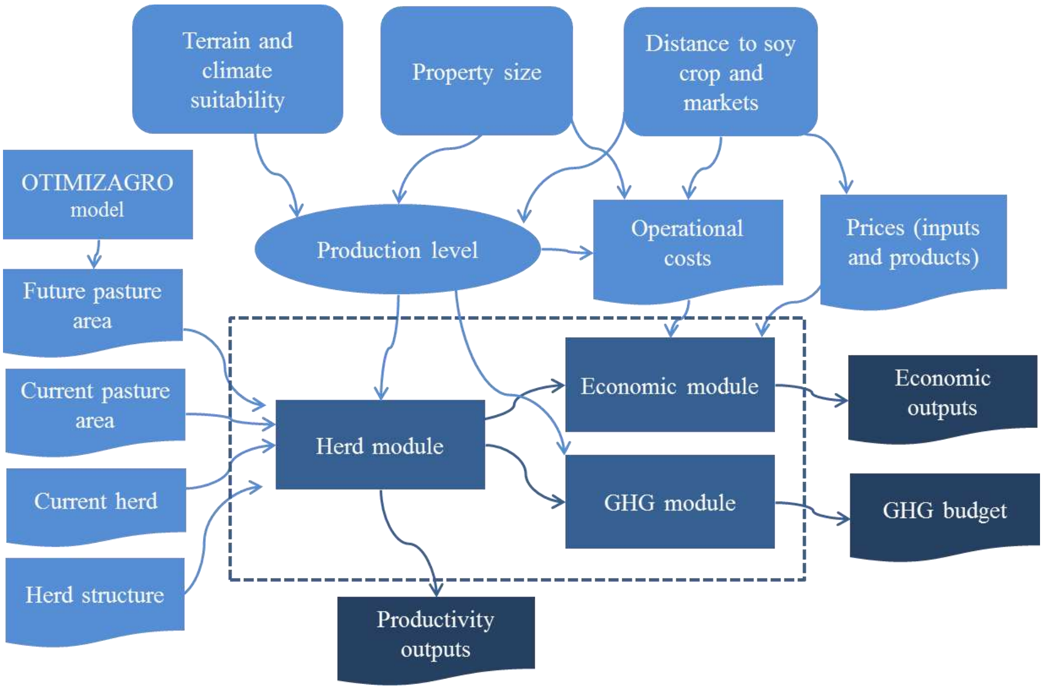

Figure 1 - Overall flowchart of the SimPec model, depicting main inputs (light blue), outputs (dark blue), and processing modules (intermediate blue).

Table 1 - Data source used to simulate the intensification scenarios

Data source	**Data**	**Spatial unit**	**Assumptions**
Brazilian Institute of Geography and Statistics (Ibge, 2016)	Current herd	Municipality	2012's herd
	Property size structure	Municipality	Only part of the pastureland and the herd will undergo intensification. It was defined according to the proportion of properties larger than 500 ha (Figure 6).
Yearbook of Brazilian Livestock (Anualpec, 2015)	Herd structure (Table 4)	State	Municipalities' initial herd structure is the same of that of Mato Grosso.
	Operational costs (Table 5-6)	State	We consider the impact of the scale of production costs
Mato Grosso's Institute of Agricultural Economics	Spatial distribution of fedlots in 2012 (Imea, 2012)	Macroregions (Imea, 2010)	
	Corn and soy price (Imea, 2016a)	Macroregions (Imea, 2010)	Data used to calculate the costs of animal feeding in feedlot and pasture supplementation (Table 6)
	Beef sale price (Imea, 2016a)	Municipality	Prices of heifers and steers are for the harvest (December-May) and non-harvest periods (June-November) (Table 7)
Soares-Filho et al. (2016)	Initial pasture area	Municipality	
	Future pasture area	Municipality	

2.2 Mato Grosso State – a case study.

A quick glance at the biophysical characteristics and logistics (distance to markets and the soy belt) would indicate that the state of Mato Grosso in Brazil is poised for cattle intensification (Figure 2).

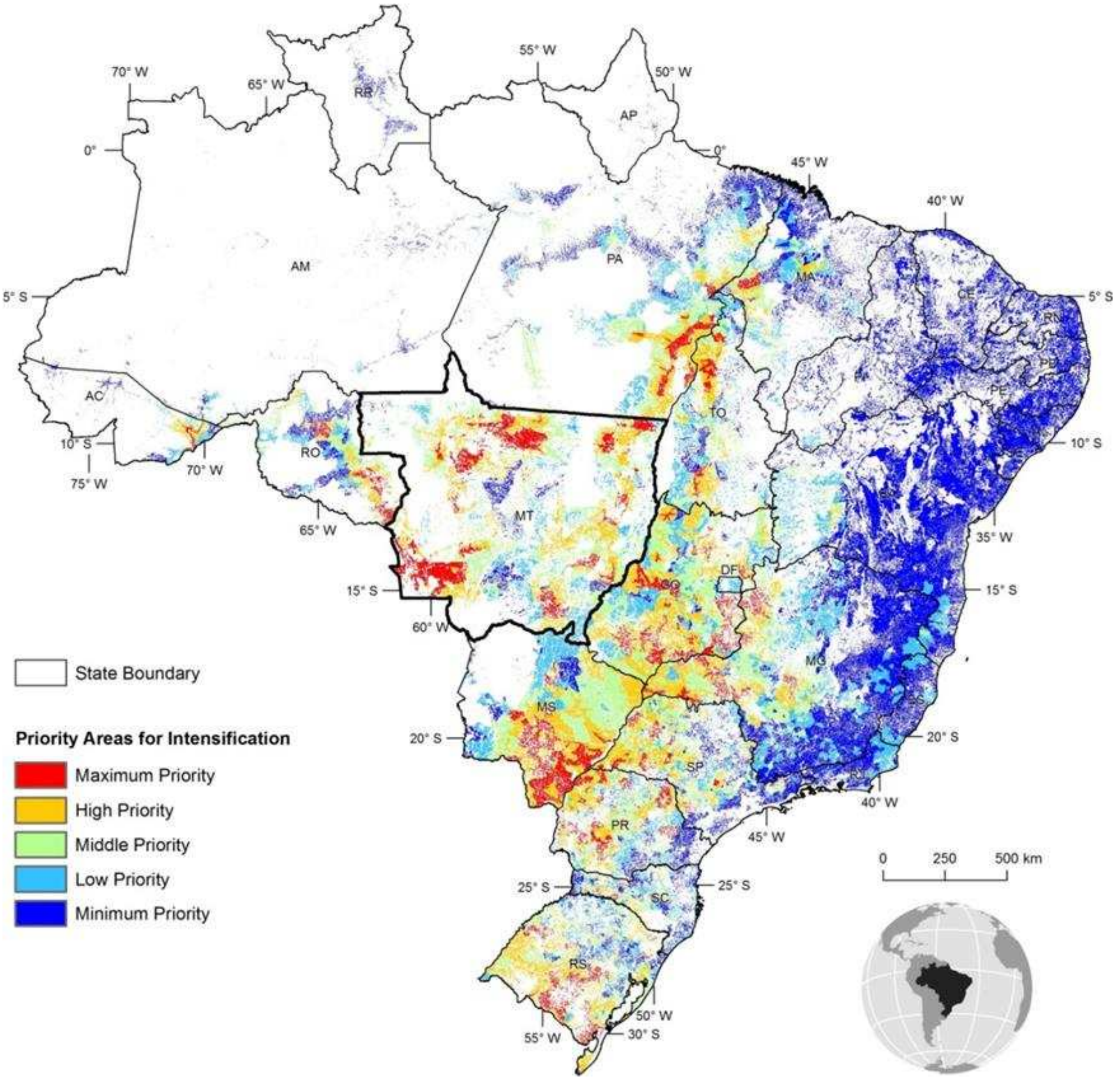

Figure 2 - Priority areas for intensification in Brazil (adapted from Barbosa et al., 2015).

With 29 million head (Ibge, 2016) (13% of the country herd) Mato Grosso is the national champion of beef production (Imea, 2016b). Recently, its beef production has steadily improved (Anualpec, 2015), especially due to a marked rise in the number animals in feedlot (Figure 3).

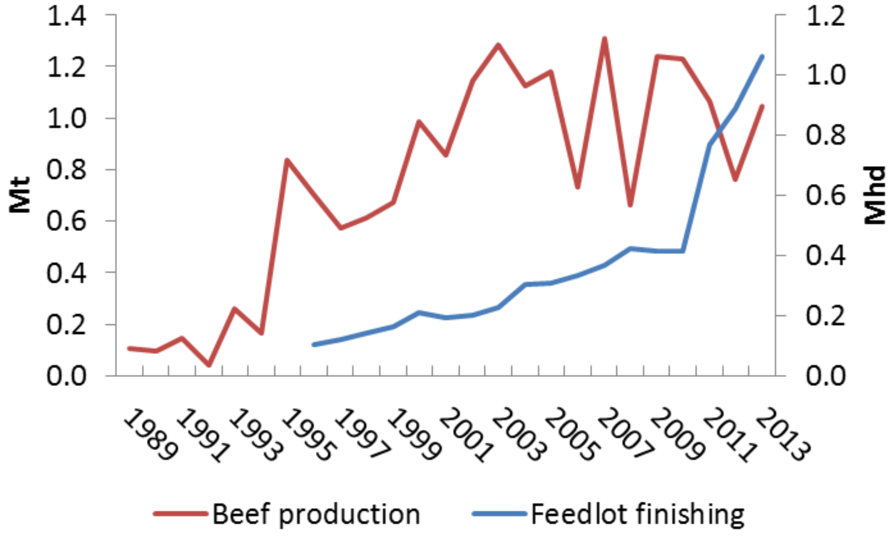

Figure 3 - Beef production (Mton) and animals finished in feedlots (Mhd – million heads) in the state of Mato Grosso (Ibge, 2006; Anualpec, 2015).

In 2014, about 1.17 million head were finished in feedlots, more than a quarter of the Brazilian confined herd (Anualpec, 2015). Yet, despite the belief that cattle ranching and deforestation have decoupled (Lapola *et al.*, 2014; Nepstad *et al.*, 2014), Mato Grosso's production continues to be largely driven by pastureland expansion where extensive ranching with low stocking rates are the rule (Figure 4).

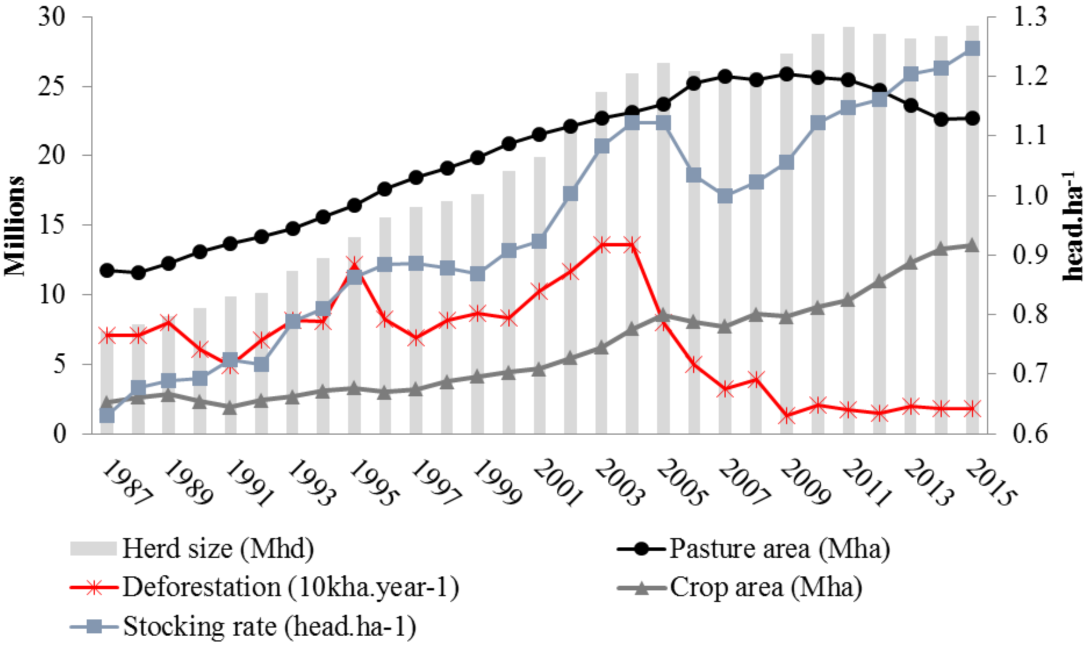

Figure 4 - Herd size, pasture and crop area, deforestation and stocking rate in the state of Mato Grosso. New pasture area is obtained by deducting croplands from the sum of deforestation from PRODES (Prodes, 2016) and LAPIG (Lapig, 2002)

2.3 Simpec model

The SimPec model, implemented using Dinamica EGO (Soares-Filho *et al.*, 2016), simulates the dynamics of a complete cycle of beef production, which includes cow-calf, steer raising, and fattening operations at a selected spatial unit, e.g. from a ranch to a jurisdictional entity, *i.e.* a municipality**.** The model uses as input the physical structure (herd, pasture area, property infrastructure) of a ranching system, along with zootechnical and agronomics coefficients, operational and investments costs, and sale prices under a specified management strategy. It then ex ante evaluates the effects of management strategies on the herd productivity, the system economics and resulting GHG emissions (Supplementary equations). The model comes with Wizard interface, making it a friendly tool for managing and planning investments in cattle ranching (Figure 5).

Relatórios

ores produtivos

de desfrute do rebanho: Informa sobre o excendente gerado) na propriedade ao longo do ano. É diretamente proporcional interna do rebanho. É influenciada por fatores como: adoção de to, indicadores zootécnicos, ganho de peso diário entre outros.

de crescimento do rebanho acumulada

ução anual de carne

Taxa de crescimento do rebanho acumulada

Updated lookup table.

Produção de carne

Lookup table.

Estratégias de manejo

2.3) Medicamentos: indicar o gasto anual (R$/cab/ano) com manejo sanitário dos animais divididos em três grupos: animais até 12 meses, animais de recria e engo rda e matrizes.

2.4) Reprodução: indicar o gasto com as matrizes no manejo reprodutivo em R$/cab/ano.

Sanidade dos animais

Data carrier for table.

id*	descricao	bezerros
1	vacinas	
2	vermifugos	

Reprodução

Data carrier for table.

Id*	Descricao
1	despesas com reproducao

Relatórios

tados econômicos

odução das tecnologias no sistema de produção, ocorre um aumento operacionais, necessitando de maiores desembolsos do fluxo de caixa sa rural. Em contrapartida, o aumento da produção (bezerros os, arrobas produzidas, animais abatidos, etc) tende a diluir os custos is fixos (depreciações e despesas fixas) fazendo com que o custo l total unitário seja menor. Esses resultados serão melhores ou piores da região (preço de insumos, de terra e da arroba), do mercado (preços e venda) e da escala de produção ou tamanho da propriedade.

estimentos: n este grupo estão incluídos os custos que representam os com: aquisição de terras, benfeitorias, máquinas, veículos, animais de banho inicial, touros, matrizes, formação de pastagens, formação de erenes e plantio de florestas.

espesas: n este grupo estão incluídos custos que representam os com compra de animais para engorda, mão-de-obra, manutenção de s, maquinas, cultivos, manejo sanitário, alimentar e reprodutivo.

ceitas: a s receitas são computadas mensalmente e constituídas pelas bezerros desmamados; bois gordos, vacas vazias descartadas, novilhas s, touros velhos para abate e bens patrimoniais como máquinas, nimais de serviço.

ultado de caixa

Investimentos

Table containing the additional data column and data.

ano*	reais_ano	reais_hectare_ano
0	19060879	2117.87544444444
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0

Despesas

Table containing the additional data column and data.

ano*	reais_ano	reais_hectare_ano
0	0	0
1	22278862....	2475.42920710179
2	22300995....	2477.88836185963
3	21904916....	2433.87964698414
4	21390552....	2376.72800211598
5	20867307....	2318.58970472879

Receitas

Table containing the additional data column and data.

ano*	reais_ano	reais_hectare_ano
0	0	0
1	31629312....	3514.36810151778
2	34283034....	3809.22604556113
3	32670799....	3630.08879005384
4	33194308....	3688.2565324619

Figure 5 - Wizard tutorial interface of SimPec.

2.4 Management scenarios

Four management scenarios are modeled. In the **HIST** scenario, historical trends in cattle productivity increases between 1996 and 2012 (Anualpec, 2015; Barbosa *et al.*, 2015) are linearly projected into the future to constitute a baseline scenario. To meet the expected target of beef production for Mato Grosso of 1.65 Mt of carcass equivalent by 2030 (Barbosa *et al.*, 2015; Mapa, 2016b), and simulate market driven growth, we designed two scenarios of intensification strategies. The first (**CAFO**) prioritizes investments in feeding supplementation (calves and steers in pasture) and feedlots for steer fattening; the second (**PASTRE**) relies more heavily on pasture restoration. These strategies are complementary – one cannot work without the other – but differ in terms of the balance between the two scenarios (Table 2). As a common practice in Brazil, our scenarios adopt feedlot finishing for steers over only the last 90 to 120 days of their lifetime, hence cattle raising continues to rely largely on pasture. Lastly, the **GOV** scenario tests the feasibility and impact of Brazil's NDC and ABC (Plano Abc, 2012; Brasil, 2015) target of restoring 30 Mha of pastureland by 2030. This extent of pastureland to be restored by both ABC and NDC plans by 2030 for the entire country was rated for the Mato Grosso state, based on Mato Grosso's potential for intensification in relation to entire country (Barbosa *et al.*, 2015) (Figure 2), and then distributed across its municipalities taking into account the regional potential for intensification based on average minimal monthly and annual precipitation as well as logistics, including distances to markets and croplands. As a result, the share of pasture to be restored in Mato Grosso municipalities totaled 6 Mha. Because this scenario also focuses on pasture restoration, we assume the same ratio for feedlot steers over the total slaughtered steers as well as productivity indices as the PASTRE scenario (Table 2). Productivity indices to be attained as the system enters an intensification mode within a management scenario are defined based on experts' recommendations (Table 2). Our study did not consider integrated systems where pasture is rotated with crops as another possible management scenario because in this case, cattle ranching is typically a byproduct of intensive crop farming.

Table 2 - Technical coefficients of modeled management scenarios

Paramenter	**Unit**	**Current**	**HIST**	**CAFO**	**PASTRE**	**GOV**
Birth rate	%	66	70	80	80	80
Mortality rate < 12 months	%	5	4	3	3	3
Mortality rate > 12 months	%	1	0.5	0.5	0.5	0.5
Replacement rate cows	%	5	10	10	10	10
Cows age at first calving	Months	47	36	36	36	36
Ratio bull/cow		1/25	1/30	1/40	1/40	1/40
Replacement rate bulls	%	5	10	10	10	10
Weight at birth	Kg	30	32	32	32	32
Weight at weaning male	Kg	180	**185**	**250**	**190**	**190**
Weight at weaning female	Kg	170	**175**	**240**	**180**	**180**
Average ration of total pasture area restored annually	%	-	**0.35**	**0.41**	**0.74**	**1.4**
Ratio of slaughtered steers finished in feedlot	%	33	**37**	**64**	**34**	**34**
Ratio of slaughtered steers finished in pasture with supplementation	%	12	**16**	**22**	**12**	**12**
Average weight of cows	Kg	420				
Average weight of bulls	Kg	550				
Age at weaning	Months	7				
Stocking rate restored pasture	AU.ha^{-1}	2.5				
ADG extensive past. dry season	kg head^{-1}day^{-1}	0.18 (Male); 0.11 (Female)				
ADG extensive past.wet season	Kg head $^{-1}$day^{-1}	0.46 (Male); 0.34 (Female)				
ADG improved past.dry season	kg head^{-1}day^{-1}	0.20 (Male); 0.15 (Female)				
ADG improved past.wet season	kg head^{-1}day^{-1}	0.60 (Male); 0.40 (Female)				
ADG pasture supplementation	kg head^{-1}day^{-1}	0.90				
ADG feedlot	kg head^{-1}day^{-1}	1.60				
SW pastures (extensive and improved)	kg	540 (Male); 390 (Female)				
SW feedlot & pasture supplementation	Kg	570 (Male)				
Carcass yield pasture	%	52 (Male); 50 (Female)				
Carcass yield pasture supplementation	%	54 (Male)				
Carcass yield feedlot	%	56				

AU – animal unit (1 AU= 450 kg live weight). ADG – average daily gain. SW – minimum slaughter live weight

Future pasture areas are simulated using OTIMIZAGRO model (Soares-Filho *et al.*, 2016). While the **HIST** scenario assumes that current deforestation rates will continue into the future, the other scenarios assume lower rates of deforestation. In all scenarios, cropland expands, compensating part of pasture expansion due to deforestation. Croplands by 2030 are set to produce 24 and 34 Mt grains of corn and soy, respectively, in order to meet national and international demands, including supplementary feeding needed for intensification in modeled scenarios (Table 3).

Table 3 - Current and future land use in Mato Grosso under modeled scenarios (thousand ha).

	Current	2030	
		Historical	**PASTRE, CAFO, GOV**
Restored Forest Code debt	0	1,426	3,544
Planted forest	60	63	66
Soy	6,265	9,841	11,016
Corn	1,923	3,476	3,930
Sugarcane	228	230	231
Pastureland	24,763	28,089	24,079

2.5 Intensification module

Simpec begins by stratifying each municipal herd into categories of gender, age, and weight according to the state distribution (Table 4).

Table 4 - Herd's structure in the state of Mato Grosso in 2012 (Anualpec, 2015).

	Number of animals (thousands)	**Average live weight (kg)**	**Proportion in the herd (%)**
Cows	8,142	420	30.3
Bulls	236	550	0.9
Heifers from 25 to 36 months	2,370	360	8.8
Heifers from 13 to 24 months	3,346	260	12.5
Female calves up 12 months	3,480	140	13.0
Male calves up to 12 months	3,776	140	14.1
Steers from 13 to 24 months	2,985	349	11.1
Steers from 25 to 36 months	1,859	418	6.9
Steers from 37 to 48 months	526	499	2.0
Steers above 48 months	126	521	0.5

The herd dynamics, or development trajectory, is then modeled as a function of a set of productive indices (Table 2) through supplementary equations S1-S7 (herd module). Initial and future pasture areas for each municipality come from the results of the OTIMIZAGRO model (Soares-Filho *et al.*, 2016), which forecasts land use. All pastures were initially included in the extensive category but with varying stock density according to current municipality data (Barbosa *et al.*, 2015). Initial feedlot capacity (*Fd*) (Anualpec, 2015) is disaggregated per municipalities using regional data. Under each scenario, the model expands and restores pastures in fixed annual rates and increases *Fd* rates according to the municipality's proximity to croplands.

The model then computes investments, operational costs and revenues from beef sales to calculate net returns (Supplementary equations S8-S11 – economic module). Investments costs include both pasture restoration and feedlot installation (Table 5). Operational costs vary as a function of property size, management system (Anualpec, 2015) and local grain prices (Imea, 2016a) (Table 5-6).

Table 5 - Operational and investments costs (US$*) used in the economic module (Anualpec, 2015).

		Extensive systems		**Improved systems**	**Source**
		small scale	**large scale**	**large scale**	
Operational costs					
Labor	$\mathrm{US\$.ha^{-1}.yr^{-1}}$	40.0	17.4	24.8	Anualpec (2015)
Mineral and protein feeding	$\mathrm{US\$.AU^{-1}.yr^{-1}}$	22.9	22.9	26.3	Anualpec (2015)
Creep feeding**	$\mathrm{US\$.head^{-1}.day^{-1}}$	-	-	0.3	
Feedlot and pasture supplementation	Varies spatially (Table 6)				IMEA (2016a)
Sanitation management	$\mathrm{US\$.AU^{-1}.yr^{-1}}$	2.6	4.8	5.6	Anualpec (2015)
Other inputs	$\mathrm{US\$.AU^{-1}.yr^{-1}}$	5.8	6.0	6.2	Anualpec (2015)
Extensive pasture maintenance	$\mathrm{US\$.ha^{-1}.yr^{-1}}$	3.2	4.3	4.3	Anualpec (2015)
Improved pasture maintenance	$\mathrm{US\$.ha^{-1}.yr^{-1}}$	-	-	237.0	Barbosa *et al.* (2014)
Infrastructure maintenance	$\mathrm{US\$.AU^{-1}.yr^{-1}}$	17.3	10.3	10.2	Anualpec (2015)
Machinery maintenance	$\mathrm{US\$.AU^{-1}.yr^{-1}}$	24.3	6.9	8.9	Anualpec (2015)
Machinery depreciation	$\mathrm{US\$.AU^{-1}.yr^{-1}}$	6.6	2.0	2.5	Anualpec (2015)
Administrative costs and taxes	$\mathrm{US\$.ha^{-1}.yr^{-1}}$	15.7	14.0	19.1	Anualpec (2015)
Investments					
Pasture restoration	$\mathrm{US\$.ha^{-1}}$			1,019.0	Barbosa *et al.* (2014)
Feedlot installation	US\$. additional confined head^{-1}			170.0	Barbosa *et al.* (2014)

*US\$= R\$ 2.35 (Average value for 2014).

**Creep feeding was used only in CAFO' scenario. It increases the weight at weaning of both male and female calves in this scenario. The cost was calculated to an average consume of concentrated feed of 0.5 kg/head/day.

Table 6 - Costs of animal feeding in feedlot and pasture supplementation regime (US\$ animal^{-1} day^{-1}). These costs were calculated using 2014 prices for corn and soy (Imea, 2016a).

Macroregions	**Pasture supplementation (Steers)**	**Feedlot**
Northwest	0.81	2.00
North	0.77	1.91
Northeast	0.85	2.04
Middle north	0.81	1.96
West	0.81	2.00
South center	0.81	2.00
Southeast	0.89	2.17

Revenues depend on beef production, carcass yield, and price locally paid during the harvest and non-harvest periods (Table 7) (Imea, 2016a) (Supplementary equation S8). Rents are provided as net present value (NPV) using an annual discount rate of 8.5% over the 18 years of the simulation period (Supplementary equation S11). Different from Bowman et al. (2012) our model treats ranching as a closed system in which there is no entry and exit of ranchers. Hence, we do not consider investments in setting up the ranch, such as land acquisition and other infrastructure, nor in selling out the herd and land to go out of business.

Table 7 - Average municipality's beef sale price (US\$ arroba^{-1}) of heifers and steers for the harvest and non-harvest periods in Mato Grosso (Imea, 2016a). Values in parentheses represent the standard deviation.

	Hervest	**Non-harvest**
Heifers	42.6 (±1.1)	46.0 (±1.1)
Steers	46.4 (±1.0)	49.6 (±1.0)

Given that intensification needs scale of production and it is influenced by the rancher business background, intensification in our model takes place only in properties equal or larger than 500 ha. We assume that 80% of the current herd and pasturelands in these properties would be available for intensification under the premises of each management scenario. This is equivalent to 15 Mha or 62% of Mato Grosso's pasturelands (Figure 6) that currently house roughly 17 Mhd. Nonetheless, all pasturelands and outputs within a municipality are considered for computing total production and average productivity under each scenario.

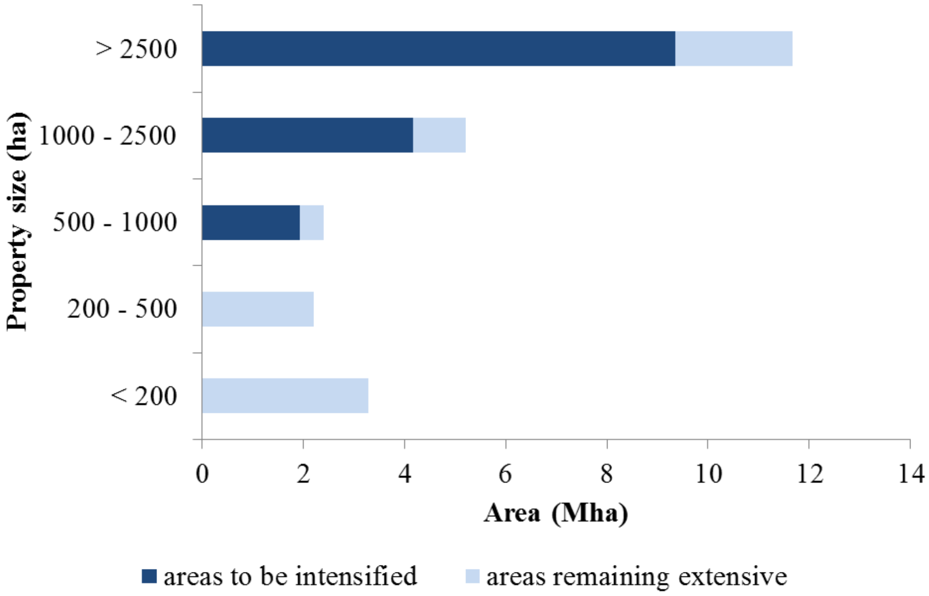

Figure 6 - Proportion of pasture area to be intensified in Mato Grosso state according to the property sizes (Ibge, 2016).

2.6 GHG bookkeeping module

GHG emissions include CH_4 from enteric fermentation and manure, N_2O from manure and fertilizer utilization as well as CO_2 from urea and lime application (Supplementary Equations S12 through S44 – GHG module). Herd emission and fertilizer coefficients uses IPCC tier 2 and 1 (Ipcc, 2006), respectively (Table 8-9). To convert CH_4 and N_2O to CO_2e we use the global warming potential for methane and N_2O, 28 and 265 respectively.

We assume that restored pasture increases carbon content over a period of 20 years. The coefficient for carbon fixation in soil comes from Maia et al. (2009). These authors analyzed the effect of pasture management on soil organic carbon (SOC) in the states of Mato Grosso and Rondônia. In this study, the authors analyzed the SOC dynamic for the transitions 1) native vegetation (NV) to degraded pasture (DP) and 2) native vegetation to improved pasture (IP). While the transition NV-DP loses SOC at 0.28 ton $C.ha^{-1}.yr^{-1}$, NV-IP increases SOC at 0.61 ton $C.ha^{-1}.yr^{-1}$. To be conservative, we assume that the degraded pastures to be restored are in equilibrium, thus without further loss of carbon. When restored these pastures have the potential to regain carbon (0.28 ton $C.ha^{-1}.yr^{-1}$) through the transition NV-DP and additionally through the transition NV-IP (0.61 ton $C.ha^{-1}.yr^{-1}$). Hence, we assume 0.89 (0.28+0.61) ton $C.ha^{-1}.yr^{-1}$ as the total gain in carbon soil.

Table 8 - Parameters for calculating GHG emissions

Symbol	Description	units	Value	source
MK	Milk production	$kg.day^{-1}$	3.7	
MF	Milk fat content	%	3.5	
CPM	Milk protein content	%	3.2	
Bmax	Maximum CH_4-producing capacity of the manure	m^3 CH_4 .kg of volatile solid excreted^{-1}	0.1	(Ipcc, 2006)
MCF	Methane conversion factor for manure management	%	0.015	(Ipcc, 2006)
UE	Urinary energy	fraction of gross energy intake	0.04	(Ipcc, 2006)
ASH	Ash content of manure	fraction of dry matter feed intake	0.08	(Ipcc, 2006)
Nfert	N fertilizer	$kg.ha^{-1}$	100	
FR_fvol1	Fraction N fertilizer (urea) that volatilizes	kg N volatilized. kg of N applied^{-1}	0.3	(Alves, 2014)
FR_fvol2	Fraction of N fertilizer (other sources) that volatilizes	kg N volatilized. kg of N applied^{-1}	0.1	(Ipcc, 2006)
FR_mpvol	Fraction of N (urine and dung) deposited by grazing animals that volatilizes	kg N volatilized. kg of N deposited^{-1}	0.2	(Ipcc, 2006)
FR_mcvol	Fraction of N (urine and dung) deposited by confined animals that volatilizes	kg N volatilized. kg of N deposited^{-1}	0.3	(Ipcc, 2006)
FR_lch	Fraction of all N added to soils that is lost through leaching and runoff	kg N. kg of N additions^{-1}	0.3	(Ipcc, 2006)
EF_lch	Factor for N_2O emissions from N leaching and runoff	kg N_2O_N .kg N leaching/ runoff^{-1}	0.0075	(Ipcc, 2006)
EF_vol	Factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces	kg N_2O_N kg NH_3_N + NO_X_N volatilized^{-1}	0.010	(Ipcc, 2006)
EFfertd	Direct N_2O emissions for N additions from fertilizers	kg N_2O_N. kg N applied^{-1}	0.1	(Ipcc, 2006)
EFd	Factor for direct N_2O emissions from manure deposited in pasture as dung	kg N_2O_N. kg N excreted^{-1}	0.01	(Alves, 2014)
EFu	Factor for direct N_2O emissions from manure deposited in pasture as urine	kg N_2O_N. kg N excreted^{-1}	0.02	(Alves, 2014)
EFm	Factor for direct N_2O emissions from manure management	kg N_2O-N. kg N^{-1}	0.02	(Ipcc, 2006)
$EFCO_2u$	Factor for CO_2 emission from urea	kg C. kg urea^{-1}	0.20	(Ipcc, 2006)
C_lm	Lime added to soil	kg ha^{-1}	2000	
EF_lm	Emission factor of lime application	kg C. kg limestone or dolomite^{-1}	0.125	(Ipcc, 2006)

Table 9 - Properties of different animal feeding regimes

	Unit	Extensive pasture	Improved pasture	Pasture supplementation	Feedlot
Protein content in dry matter	%	8[a]	11[b]	12[c]	14
Digestibility of dry matter	%	55	59	72	79
Methane conversion rate	%	6.5[d]	6.0	4.0	3.0

[a](Euclides *et al.*, 2009)
[b](De Andrade Gimenes *et al.*, 2011)
[c](Cota *et al.*, 2014)
[d](Ipcc, 2006)

Increasing pasture yields raises biomass of grass forages. Nevertheless, we did not consider this gain because pasture restoration also entails biomass losses from eradicated regrowth that often populates the so-called “degraded pasturelands”, outdoing in many cases biomass gain in grass forages (Wandelli e Fearnside, 2015).

2.7 Sensitivity analysis

2.7.1 Economic uncertainty

To estimate uncertainty bounds for our economic estimates, we examined the model response to variation in prices of beef, fertilizers, and grains at the farm gate. We assumed a ± 10% variation in costs of pasture restoration and maintenance alongside feeding confined and semi-confined animals and a variation of ± 9.2 in beef sale prices following the deviation from 1997 to 2016 (Table 10; Figure 7).

Table 10 - Sensitivity of Net Present Value (%) to changes in feeding and pasture maintenance costs along with beef sale prices.

	Variations in inputs cost and prices (%)	Output Net Present Value (%)			
		Historical	PASTRE	CAFO	GOV
Feeding	±10	±1.6	±1.6	±2.7	±2.0
Pasture maintenance	±10	±1.4	±2.5	±1.2	±4.9
Beef sale price	±9.2	±32.4	±26.7	±31.2	±37.8

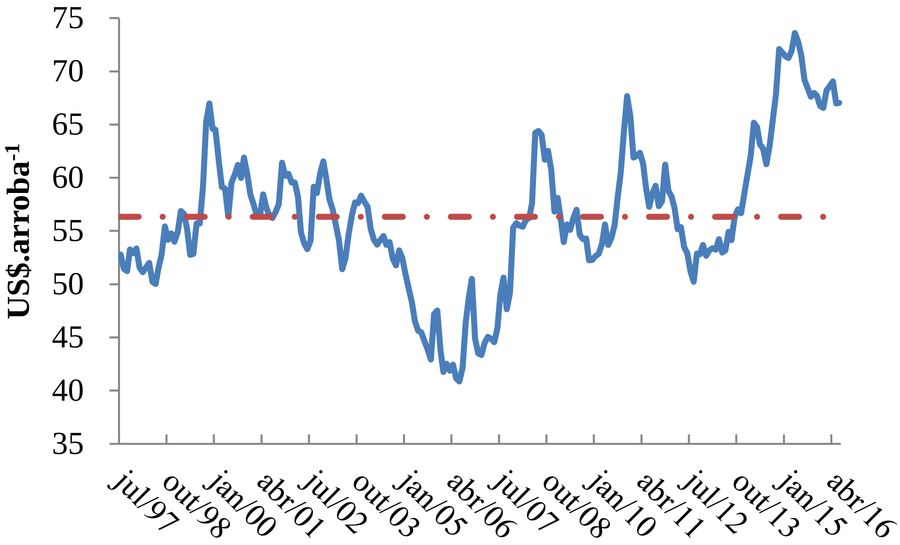

Figure 7 - Beef price for producers. Values are deflated by IGP-DI index (FGV, 2016).

Beef sale price is the variable that most affected the profitability of ranching (Table 10). Thus, we used this variation as the uncertainty bounds for the model economic outputs (Table 12-13).

2.7.2 GHG emissions uncertainty

To develop an envelope of confidence for the model output emissions, we compared different sources for GHG coefficients for carbon fixation in soil. We consider the rate of SOC in improved pastures to be within the lower and upper bounds of 0.27 and 1.12 ton $C.ha^{-1}.yr^{-1}$, respectively, according to Lal. et al. 2006.

3 Results

3.1 Productivity

Under the **HIST** scenario, the herd will grow at mean annual rate of 1.6%, reaching a total of 37 Mhd (Figure 8) and with a stock density of 0.94 AU/ha (0.9% yearly growth), covering 28 Mha of pasturelands by 2030. Even under the historical assumptions, at least 1.7 Mha of pastures will need to be renovated to accommodate this herd (Table 11). Steers finished in feedlots will total 20% of slaughtered animals, 18% more than in 2012 (Figure 9), and pasture plus supplementation, following the historical trend, will comprise 8% of the slaughtered animals. Although, productivity will increase by 34%, on average, beef production of 1.5 Mt will be below the target expected for Mato Grosso (Barbosa *et al.*, 2015).

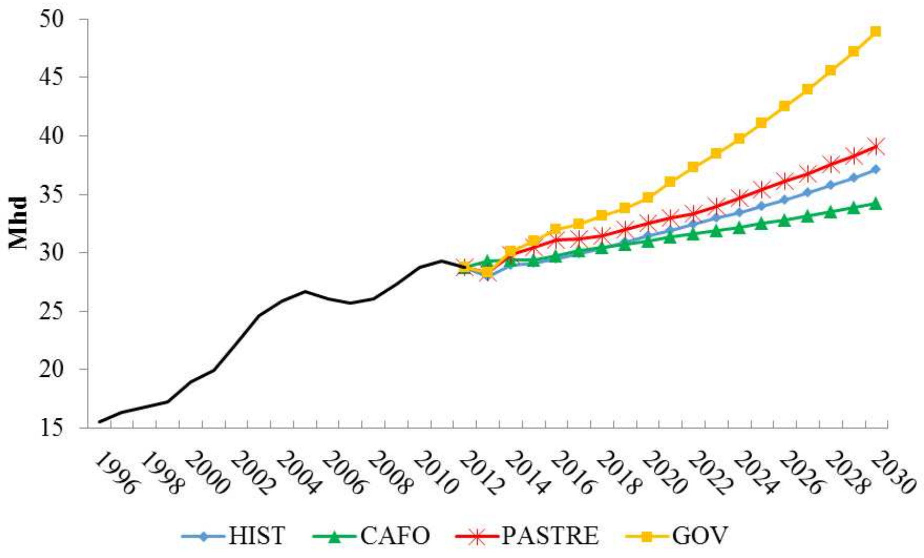

Figure 8 - Herd's historical evolution (from 1996 to 2012) and under modeled scenarios

To meet the future planned production of 1.6 Mtons by 2030 (Barbosa *et al.*, 2015), a policy scenario focused on pasture restoration **(PASTRE)** would need to promote the renovation of 3.3 Mha of pasturelands, considering the contraction of these areas due to cropland expansion to 24 Mha by 2030. Under the **PASTRE** scenario, stock density will grow at a mean annual rate of 2.1%, reaching 1.14 AU/ha by 2030. The number of animals in confinement and semi-confinement operations will steadily increase alongside the reduction of slaughter age (Figure 9-10). These improvements will enable pasture productivity (arroba ha^{-1}) (1 arroba= 15 kg of carcass) to increase by 70%. As a result, the herd will grow to 39 Mhd (Figure 8).

Table 11 - Herd module outputs.

Model Results	Unit	Current	2030			
			HIST	**CAFO**	**PASTRE**	**GOV**
Herd						
Number of animals	Mhd	28.74	37.40	34.30	39.10	48.90
Number of slaughtered animals	Mhd	5.48	7.44	8.22	8.25	9.87
Steers finished in feedlot	Mhd	0.91	1.46	2.66	1.45	1.81
Steers finished in pasture with supplementation	Mhd	0.33	0.61	0.90	0.52	0.64
Average age at slaughtering (Steers and heifers)	Months	41.10	35.20	29.30	34.90	34.70
Productivity	arroba.ha^{-1}	3.20	4.30	5.53	5.53	6.64
Productivity	arroba.AU^{-1}	3.80	4.60	5.30	4.80	4.70
Meat production	Mt carcass	1.10	1.50	1.60	1.60	2.00
Pasture						
Total pasture area	Mha	24.80	28.10	24.10	24.10	24.10
Improved pasture area	Mha	-	1.90	1.80	3.20	6.00
Average stocking rate	AU.ha^{-1}	0.80	0.94	1.04	1.15	1.42

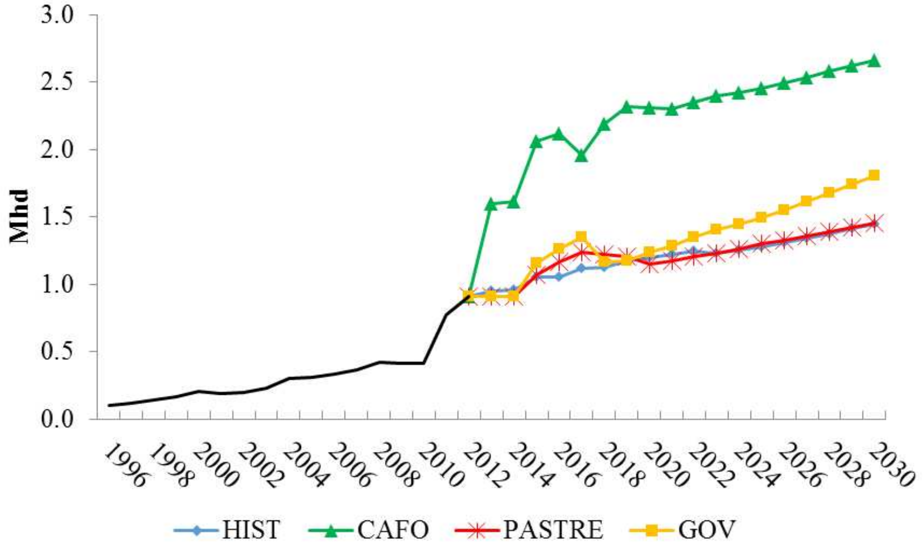

Figure 9 - Modeled trajectories of animals finished in feedlot in Mato Grosso.

Conversely, in the **CAFO** management scenario, this same level of production would be met with a herd of only 34 Mhd on 24 Mha of pasturelands, of which 1.8 Mha will need to be renovated (45% less than that of **PASTRE**). Larger shares of animals terminated earlier than 30 months in feedlots (32% of slaughtered animals) and semi-confinement (11% of slaughtered animals) alongside greater beef productivity per animal (5.3 arroba.AU^{-1}) will be responsible for this larger production from a smaller herd.

On the other hand, if Brazil implements its pasture restoration target (GOV scenario), the herd will be compelled to grow to 49 Mhd by 2030 resulting higher stock density of 1.4 AU.ha^{-1} (3.4% yearly growth) needed to pay back investments in pasture restoration. Under the productivity set by GOV, this size of herd will produce 2.0 Mt carcass weight by 2030, exceeding projected demand by 25 percent.

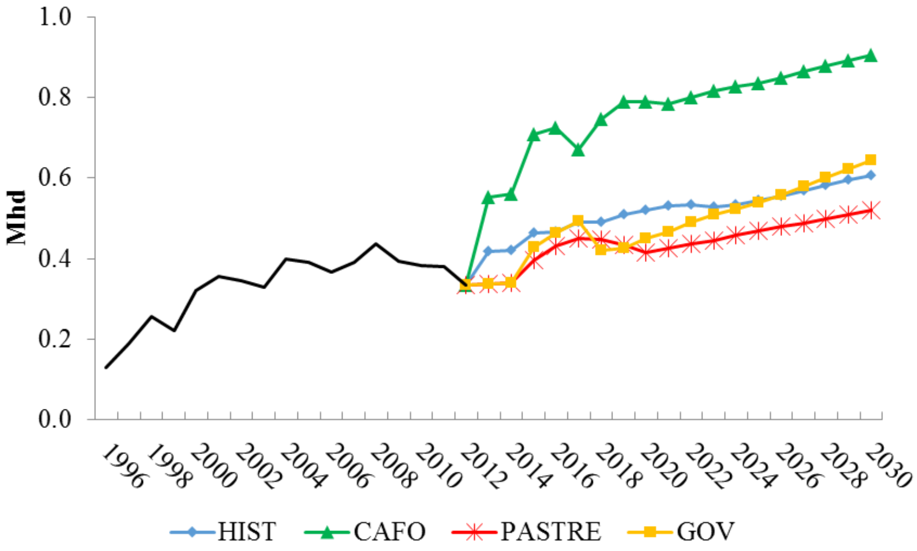

Figure 10 - Modeled trajectories of animals finished pasture supplementation in the state of Mato Grosso.

3.2 Investments and economic returns

Pasture restoration accounts for the largest share of investments in any of the scenarios. It follows then that the highest absolute value of investment will occur in the GOV scenario, which has the most area under reformation, followed by PASTRE, CAFO and HIST (Table 12). However, the lower resulting productivity in HIST, where there is the least intensification effort, will result in higher marginal investment. In CAFO, the overall investments are 43% lower than PASTRE for the same productivity per hectare. As the system intensifies, operational costs also increase due to supplemental feeding and pasture maintenance. The larger share of grains in animal feeding, higher the operational cost per animal, as in CAFO. Nevertheless, increased productivity more than compensates for greater operational costs (Table 12) (Figure 11). In the scenarios that favor pasture restoration, cost per head is lower. However, larger number of animals and cost of pasture maintenance increases total production costs, and thus costs per hectare, pushing it 7% higher than that of CAFO. In all scenarios, the return on investments is positive for most municipalities. In sum, the most economically viable scenario is the CAFO with a NPV 27% greater than that of the PASTRE (Table 13).

Table 12 - Economic module outputs. Values in parenthesis are the uncertainties bounds of estimates.

Model Results	**Unit**	**Current**	**2030**			
			HIST	**CAFO**	**PASTRE**	**GOV**
Economic indices						
Investment - pasture restoration*	US$ billion	-	1.86	1.82	3.32	6.10
Investment - feedlot installation*	US$ billion	-	0.07	0.19	0.10	0.16
Operational costs**	US$.ha^{-1}	108.00	171.00	212.00	236.00	328.00
Operational costs**	US$.head^{-1}	111.00	128.00	142.00	130.00	133.00
Profit margin**	US$.ha^{-1}	50.77	58.73 (±18)	101.79 (±25)	83.44 (±24)	86.26 (±29)

*Values accumulated over studied period

** Average values for Mato Grosso in the last year of the simulation.

Table 13 - Net Present Value (US$ ha^{-1}) for modeled management scenarios. Values in parenthesis are the uncertainties bounds of estimates.

	Net Present Value (US$ ha^{-1})
HIST	466.80 (±32%)
CAFO	767.61 (±27%)
PASTRE	605.22 (±31%)
GOV	528.58 (±38%)

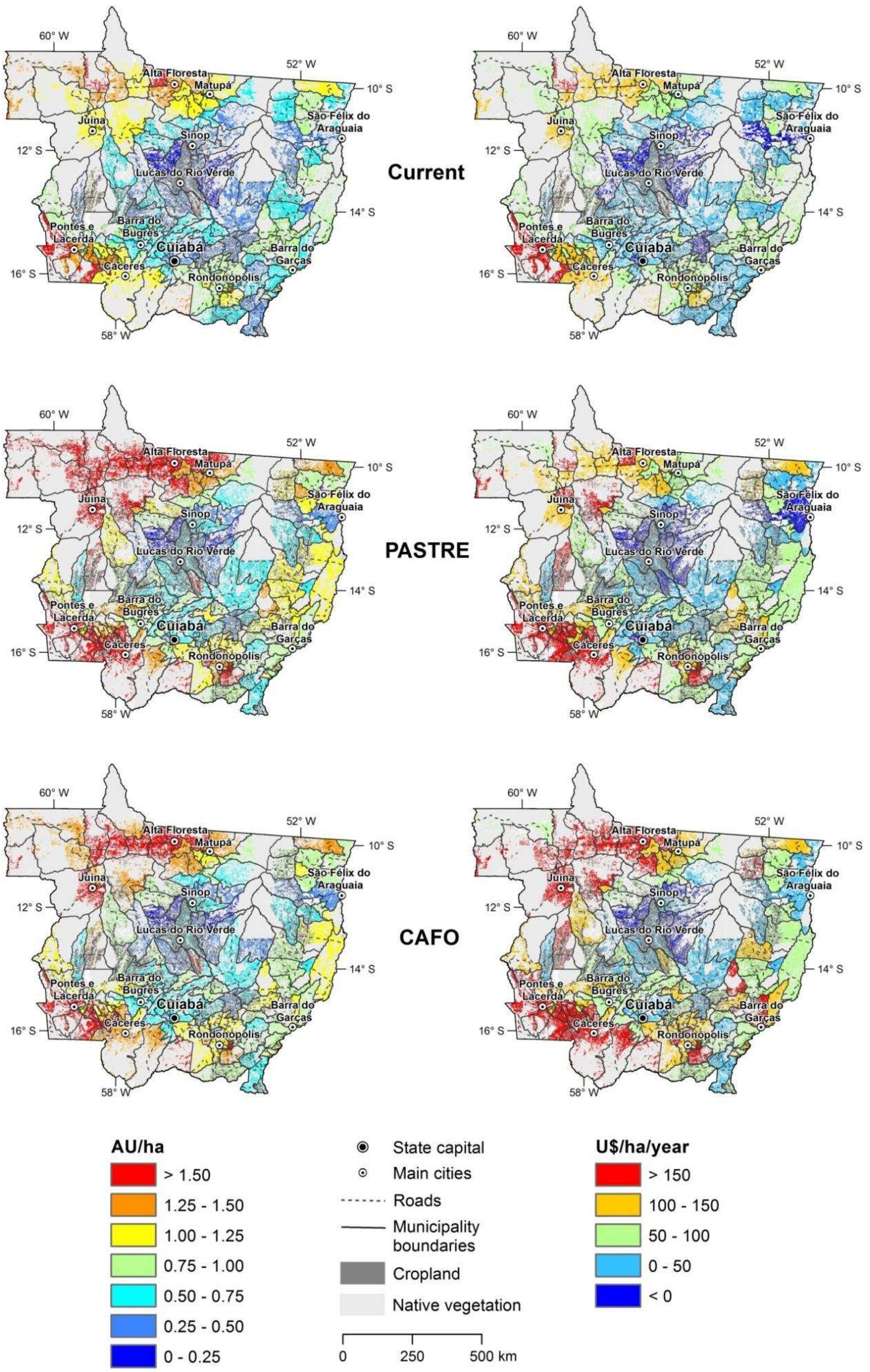

Figure 11 - Current and modeled stock densities (AU/ha) and Profit Margin (US$/ha/yr) by 2030 across Mato Grosso.

3.3 GHG emissions

3.3.1 Enteric emissions

Livestock's major GHG source is methane from enteric emissions. As of 2012, Mato Grosso herd emitted 49 $MtCO_2e$ (Figure 12).

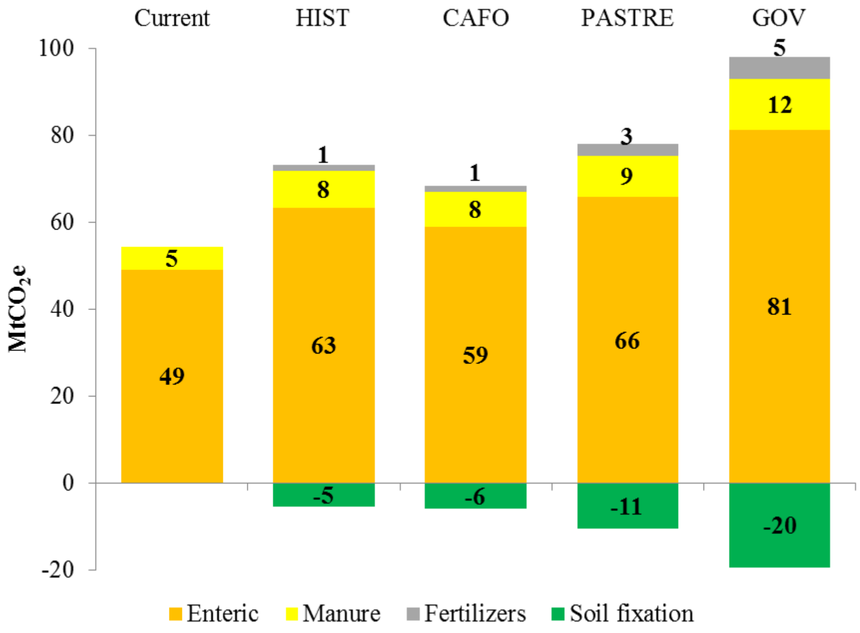

Figure 12 - GHG balance per source under modeled scenarios currently and by 2030.

This number is poised to rise as the herd grows, hence the largest emissions will occur under the **GOV** due to its biggest herd. Conversely, **CAFO** will produce the same amount of beef as that of **PASTRE** with 10% lower enteric emissions (Table 14). This lower CH_4 enteric emission in the **CAFO** scenario is due to not only to a smaller herd but also to higher beef productivity and hence earlier slaughtering (Figure 13) that compensates larger emission per head, as supplementing grains to animals has higher energetic efficiency than feeding with grass. As a result, each kg of beef produced in **CAFO** emits 11% to 16% less methane compared to those of **PASTRE** and **HIST**, respectively (Table 14).

Table 14 - GHG module outputs. Values in parenthesis are the uncertainties bounds of estimates.

Model Results	**Unit**	**Current**	**2030**			
			HIST	**CAFO**	**PASTRE**	**GOV**
GHG emissions						
Enteric CH_4	$MtCO_2e$	49.1	63.4	58.9	65.8	81.3
Manure CH_4	$MtCO_2e$	1.0	1.3	1.2	1.4	1.7
Manure N_2O	$MtCO_2e$	4.2	7.1	6.8	7.9	10.0
Fertilizers N_2O	$MtCO_2e$	-	1.0	1.1	1.9	3.6
Fertilizers CO_2**	$MtCO_2e$	-	0.4	0.4	0.8	1.4
Sequestration CO_2	$MtCO_2e$	-	5.7	5.8	10.6	19.5
GHG budget	$MtCO_2e$	54.3	67.8 (±3)	62.6 (±3)	67.2 (±5)	78.5 (±9)
Relative GHG emissions						
Enteric CH_4	kg CO_2e.kg carcass^{-1}	45.1	42.7	36.0	40.1	41.3
	kg CO_2e.head^{-1}	1,819.0	1,708.0	1,719.0	1,683.0	1,661.0
N_2O (manure and fertilizers)	kg CO_2e.kg carcass^{-1}	4.3	5.5	4.8	6.1	7.0
GHG budget	kg CO_2e.kg carcass^{-1}	49.8	45.7 (±1.7)	38.2 (±1.7)	41.0 (±3.1)	39.9 (±4.7)

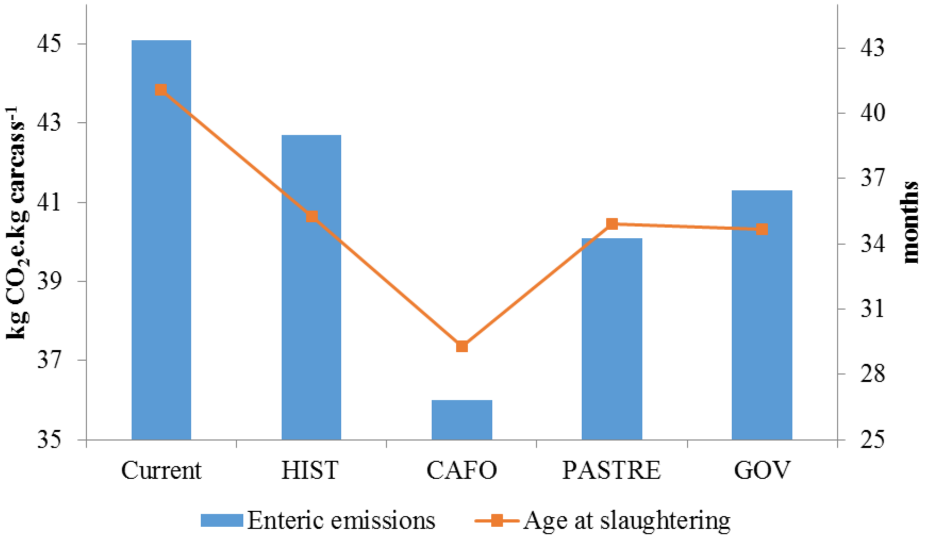

Figure 13 - Methane enteric emissions versus age at slaughtering of animals currently and by 2030 in the modeled scenarios.

3.3.2 Manure emissions

Emissions from manure is virtually proportional to the herd size, although supplementary feeding with higher protein content both in CAFOs and improved pasture increases the ratio between manure/enteric from the current 8% to 11-12% by 2030 in modeled scenarios. In turn, N_2O participation in manure emissions rises from 80% to 85% in all scenarios (Table 14).

3.3.3 Emissions from fertilizers

Pasture renovation and subsequent maintenance over time will require a substantial use of fertilizers, increasing as a result GHG emissions in intensified systems. Total emissions by 2030 will therefore be proportionally to the area of pastured renovated. In this respect, in the **GOV** scenario, emissions from fertilizer utilization will amount to 3.6 $MtCO_2e$ $year^{-1}$ by 2030, tantamount to 4.5% of total emissions, of which CO_2 emissions from lime and urea represents 30% with the remainder coming from N_2O emissions. In turn, emissions from fertilizers in the **PASTRE** and **CAFO** scenarios will account for 2.8% and 1.8% of their total emissions, respectively (Table 14).

3.3.4 Soil sequestration

We estimate that the reformation of 6 Mha of pastures in the **GOV** scenario will fix a total 19±9 $MtCO_2e$ in the soils by 2030. Even so, in both **GOV** and **PASTRE**, only 0.45 units of CO_2e will be mitigated for each additional unit emitted from 2012, while for **CAFO** scenario, this ratio will be 0.42 and only 0.29 for the **HIST** scenario (Table 14).

3.3.5 GHG budget

Increase in beef production in any of the modeled scenarios will raise GHG emissions (Table 14, Figure 14). The **GOV** scenario, despite large sequestration of carbon in the soil, typifies the worst-case. On the opposite, net emission will be lowest in the **CAFO**. This scenario will produce the same amount of beef of that the **PASTRE** with net emissions 7% lower than those of the latter scenario thanks to lower emissions coefficient per unit of beef produced, *i.e.* 38.2 kg CO_2e per kg of beef versus 41.0 kg CO_2e per kg carcass of the

PASTRE. In this respect, the **HIST** scenario stands as the worst-case. By 2030, each kg of beef produced within this scenario will emit 45.6 kg CO_2e, a reduction of only 8% in relation to 2012.

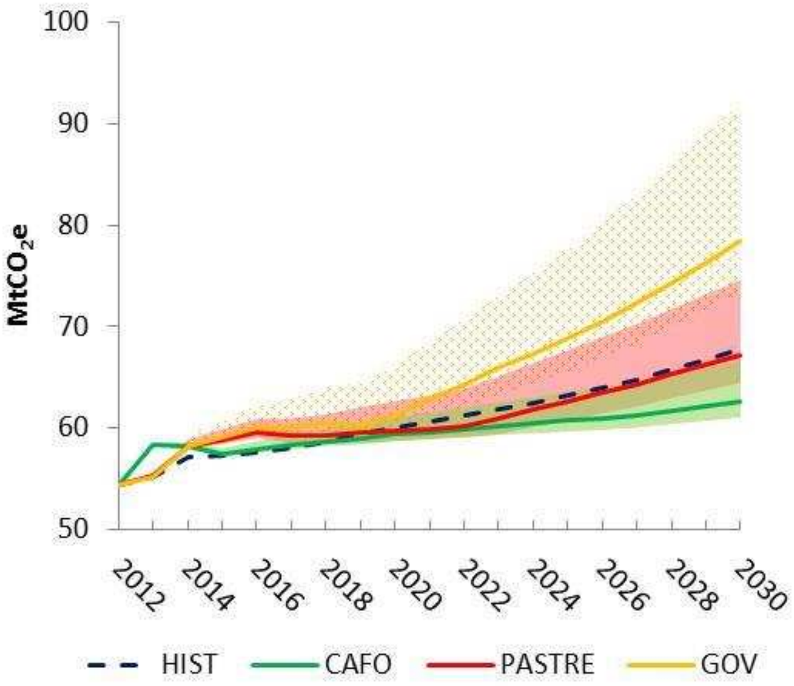

Figure 14 - Net GHG emissions under modeled scenarios. Shadow areas depict uncertainty bounds in CAFO, PASTRE and GOV scenarios.

4 Discussion and conclusion

Because a nutritional strategy based solely on pasture management faces natural constraints in the dry season when grass production is low, supplementary grain feeding both in semi-confinement and confinement operations is key to maintain animal weight, thereby decreasing slaughter age. In addition to the economic advantage of pasture supplementation and feedlot operations (Table 12-13; Figure 11), feedlots' higher energy efficiency is central to reduce GHG emissions from cattle both by diminishing the herd lifespan, hence emission lifecycle, as well as the herd size. Other environmental or social externalities apart (Werth *et al.*, 2014), feedlot also allows additional emission reductions by adequate reutilizing manure (Gerber *et al.*, 2013; Herrero *et al.*, 2016) to generate bioenergy (Palermo e Freitas, 2014) or in place of synthetic fertilizers (Gerber *et al.*, 2013).

Although improved tropical pasturelands are sinks of carbon (Maia *et al.*, 2009; Braz *et al.*, 2013; Gerber *et al.*, 2013), our results belie that these sinks could compensate marginal emissions due to higher stock densities (Barioni *et al.*, 2016). Our results suggest that only 45% of marginal emissions were mitigated by carbon fixation in soil in the scenarios of large pasture restoration, *i.e.* PASTRE and GOV. Here, we considered a fixed rate of carbon accumulation over the simulated time-period. However, there are many uncertainties regarding a wide array of factors that influence the rate of carbon accumulation in soils, such as climate, soil type, and management systems (Maia *et al.*, 2009; Smith, 2014). In addition, carbon accumulation in soils asymptotically tends to a threshold equilibrium within 20 years after pasture restoration (Ipcc, 2006; Smith, 2014), beyond which net will emissions will rise more steeply due to the continued growth of the herd. Still, carbon fixation will be effective as long as pastures remain productive. This implies, however, the continued utilization of fertilizers, bringing into question the impacts from high demands for N, P and other nutrients on the limited world reserves (Cordell e Neset, 2014; Sattari *et al.*, 2016) as well as associated GHG emissions (Tilman *et al.*, 2011).

Economic gains from cattle intensification naturally depend on beef prices along with local costs of corn and soy inputs. The latter are the lowest in Mato Grosso, since it is the largest national producer of grains (Cepea, 2016; Imea, 2016b). Regarding beef prices, our sensitivity analyses indicate that net revenues may fluctuate as much as 38% as a function of 9% variation in beef prices. Aside from the recent spike in beef prices (Figure 7), historically prices have declined from the seventies (De Zen e Barros, 2005), not to mentioning rising production costs. Nowadays, ranchers face increasing competition not only within the sector but also from other meat producers. By escalating production, intensification, instead of ensuing higher rents to ranchers, may exacerbate such a competition, perversely shrinking profit margins at the farm gate (Leonard, 2014), particularly in a scenario that production exceeds demand, such as the GOV. Therefore, regardless whether consumption of beef is approaching a global peek (Vranken *et al.*, 2014), large-scale pasture restoration appears to incur in greater economic risk given the high investment costs of this undertaking and the new volatility in both input and output prices (Table 12-13).

Contrary to results from previous studies (De Oliveira Silva *et al.*, 2016), increasing beef production will lead to an overall rise in GHG emissions from the cattle sector within a foreseeable future. Only a smaller and more productive herd could avert such an outcome. Rather than pasture restoration, investments in feedlots along with complementary strategies are more likely to prompt better economic, productive, and, in particular, environmental outlooks for the cattle sector in Brazil. If we are to continue to base our diet on beef, we should contemplate that grass-fed beef poses a tremendous impact to environment. In view of our results, Brazil's should review its climate mitigation policy, since large-scale pasture restoration, instead of reducing GHG emissions, threatens the success of Brazil's Nationally Determined Contribution.

5 Supplementary equations

The dependence between the equations for simulating the herd dynamics, economics of ranching and GHG emissions are depicted in Figure 15.

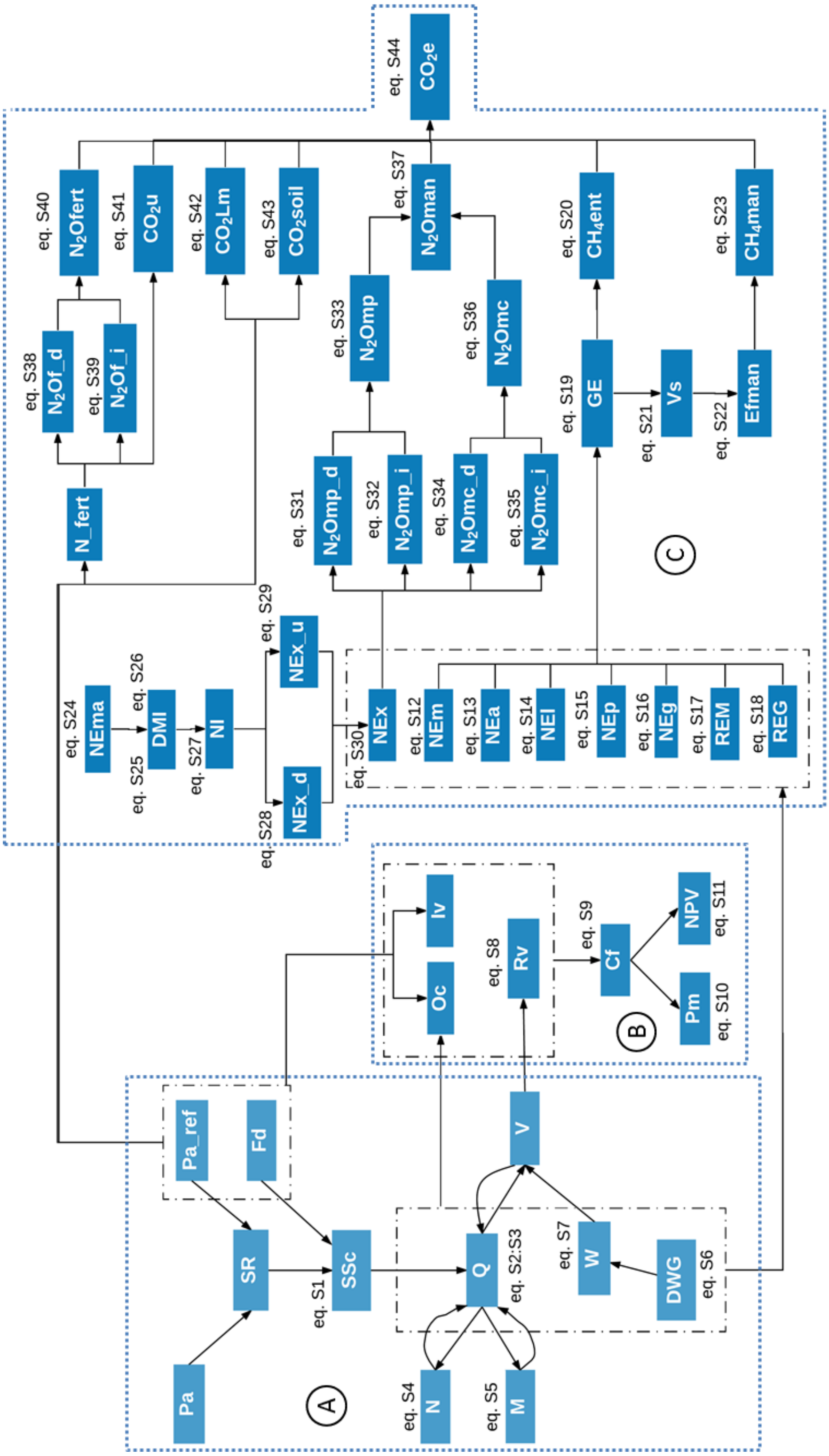

Figure 15 - SimPec equation flowchart. A - Herd module, B - Economic module and C - GHG emissions modules.

5.1 Herd dynamic module

The herd's dynamic is a function of zootechnical coefficients and the system carrying capacity (SSc), as follow:

$$\mathrm{SSc}_{s,m,t} = \left[\mathrm{SR}_{s,m,t} \times \left(\mathrm{Pa}_{s,m,t}\text{-}\mathrm{Pa\_ref}_{s,m,t}\right)\right] + \left[\mathrm{SR\_imp} \times \mathrm{Pa\_ref}_{s,m,t}\right] + \mathrm{Fd}_{s,m,t} \qquad \text{(eq. S1)}$$

where s is the management scenario, *m* municipality, *t* time (month). *SSc* is the system carrying capacity (AU); *SR* refers to extensive pasture stocking rate (AU ha^{-1}); *Pa* is the total pasture area (ha); *Pa_ref* refers to restored pasture area (ha); *SR_imp* is the improved pasture stocking rate (AU ha^{-1}); *Fd* is the average number of confined animals (AU). *SSc* is updated every 12 months.

The number of animals in the herd is updated monthly according to (eq. S2).

$$\mathrm{Q}_{s,m,t} = \sum_{c} \left(\mathrm{Q}_{c,s,m,t-1} + \mathrm{N}_{s,m,t} - \mathrm{M}_{s,m,t} - \mathrm{V}_{c,s,m,t}\right) \qquad \text{(eq. S2)}$$

where s is the management scenario, *m* municipality, *t* time (month) and *c* animal categories (1 = cows, 2 = bulls, 3 = male calves, 4 = female calves, 5 = steers on extensive pasture, 6 = heifers on extensive pasture, 7 = steers on improved pasture, 8 = heifers on improved pasture, 9 = steers supplemented in pasture and 10 = steers in feedlot). *Q* refers to the number of animals in the herd; *N* is the number of animal births (eq. S4); *M* is the number of animal deaths (eq. S5) and *V* is the number of animals sold.

Every 12 months, the herd size is adjusted as a function of *SSc* by altering the number of cows (eq. S3).

$$\mathrm{Q}_{c=1,s,m,t} = \mathrm{Q}_{c=1,s,m,t} + \left[\left(\mathrm{Cw} \times \mathrm{SSc}_{s,m,t} \times \frac{450}{\mathrm{Wu}} - \mathrm{Q}_{c=1,s,m,t}\right) \times \theta \mathrm{a}_t\right] \qquad \text{(eq. S3)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. For *c*=1, *Q* is the number of cows in the herd; *SSc* is the system carrying capacity (AU) (eq. S1); Cw refers to average perceptual of the herd composed by cows (here we used in average, 33%); *Wu* refers to the average weight of cows (kg) (Table 2) and *θa* is the cow adjustment constant (*θa*= 1 for the month when the model updates the number of cows and *θa*= 0 for others). To increase the number of cows, the model allocates heifers able to enter in reproductive phase according to pre-defined age (Table 2). The model also replaces senile cows every 12 months according to the replacement rate of cows (Table 2). The number of bulls is given by bull/cow ratio (Table 2) and the replacement of bulls is set according to replacement rate of bulls at every 12 months (Table 2). The discarded animals are thus slaughtered.

Every 12 months, new animals enter the herd by (eq. S4).

$$N_{s,m,t} = Q_{c\,=\,1,s,m,t} \times \frac{\tau n_s}{100} \times \theta b_t \qquad \text{(eq. S4)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *N* is the number of animal births. For c = 1, *Q* is the number of cows in the herd; *τn* refers to birth rate (%) (Table 2) and *θb* is the birth constant (*θb*= 1 for the month when birth takes place and *θb*= 0 for others). We assume that animals are born in august, of which 50% is male and 50% female.

Every month the number of animals that die is calculated as follow:

$$M_{s,m,t}= Q_{s,m,t-1} \times {\frac{\tau_m}{100}}\Big/_{12} \qquad \text{(eq. S5)}$$

where *s* is the management scenario, *m* municipality, *t* time (month). *M* is the number of animal deaths; *Q* is the number of animals and *τm* denotes the mortality rate (%) (Table 2).

The individual weight of animals (*W*) is updated monthly according to daily weight gain (eq. S7). For *c* = 1 (cows) and *c* = 2 (bulls), When *W* is equal to the average weight of cows and bulls, respectively (Table 2), *ADG* is 0. For c = 3 (male calves) and c = 4 (female calves), *ADG* is calculated according to (eq. S6) and for others animal category, *ADG* is defined in Table 2.

$$ADG_{c,s} = Wb + \left(\frac{Ww_{c,s} - Wb}{Aw \times 30}\right) \qquad \text{(eq. S6)}$$

where *s* is the management scenario and *c* animal category. *ADG* denotes average daily gain ($kg.animal^{-1}.day^{-1}$); *Wb* and *Ww* denotes the weight of animals at birth and at weaning (kg) respectively, while *Aw* refers to the age at weaning (months) (Table 2).

$$W_{c,s,m,t} = W_{c,s,m,\ t-1} + 30 \times ADG_{c,s,t} \qquad \text{(eq. S7)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *W* refers to the live weight of animals (kg); *ADG* denotes average daily gain ($kg.animal^{-1}.day^{-1}$) (Table 2; (eq. S6). Sales of animals occur (*V*) when the weight reaches the minimum value for slaughter (Table 2).

5.2 Economic module

To estimate the economic performance, the model computes the operational costs and investments. When animals are sold, the model records revenues, as follow:

$$\mathrm{Rv}_{s,m,t} = \sum_{c} \left(\mathrm{V}_{c,s,m,t} \times \mathrm{W}_{c,s,m,t} \times \mathrm{Cy}_{c} \times \mathrm{P}_{c,m,t} \right) \qquad \text{(eq. S8)}$$

where s is the management scenario, m municipality, t time (month) and c animal category. Rv refers to revenue (US\$); V is the number of animals sold; W refers to the live weight of animals (kg) (eq. S7); Cy carcass yield (%) (Table 2) and P is the price of beef (US\$.kg^{-1}) (Table 7).

In that way, the cash flow is updated monthly according to (eq. S9).

$$\mathrm{Cf}_{s,m,t} = \mathrm{Rv}_{s,t} - \mathrm{Oc}_{s,m,t} - \mathrm{Iv}_{s,t} \qquad \text{(eq. S9)}$$

where s is the management scenario, m municipality, t time (month). Cf denotes the cash flow (US\$); Rv refers to revenue (US\$) (eq. S8); Oc are the operational costs (US\$) (Table 5-6) and Iv is the investment costs (pasture restoration and feedlot installation costs) (US\$).

$$\mathrm{Pm}_{s,m,t} = \mathrm{Rv}_{s,m,t} - \mathrm{Oc}_{s,m,t} \qquad \text{(eq. S10)}$$

where s is the management scenario, m municipality, t time (month). Pm refers to profit margin (US\$); Rv refers to revenue (US\$); and Oc is the operational costs (US\$) (Table 5-6).

$$\mathrm{NPV}_{s,m} = \sum_{t=1}^{n} \left(\frac{(\mathrm{Rv\text{-}Iv\text{-}Oc})_{s,m,t}}{\left(1 + \frac{r}{100}\right)^{t}} \right) \qquad \text{(eq. S11)}$$

where s is the management scenario, m municipality, t time (month), and n is the number of months of simulation. NPV is the net present value (US\$); Rv refers to revenue (US\$) (eq. S8); Oc is the operational costs (US\$) (Table 5-6); Iv is the investment (pasture restoration and feedlot installation costs) (US\$) and r is the rate of return (%).

5.3 GHG module

5.3.1 CH_4 emissions from enteric fermentation

The enteric emissions of methane are calculated according to IPCC's tier 2[12], as follow:

$$\mathrm{NEm}_{c,s,m,t} = 0.322 \times \mathrm{W}_{c,s,m,t}{}^{0.75} \times \mathrm{Q}_{c,s,m,t} \qquad \text{(eq. S12)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *NEm* is the net energy required for maintenance animal (MJ day^{-1}); *W* refers to the live weight of animals (kg) (eq. S7); *Q* refers to the number of animals (eq. S2).

$$\mathrm{NEa}_{c,s,m,t} = \mathrm{C}_c \times \mathrm{W}_{c,s,m,t}{}^{0.75} \times \mathrm{Q}_{c,s,m,t} \qquad \text{(eq. S13)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *NEa* denotes the net energy for animal activity (MJ day^{-1}); *C* corresponds to animal's feeding coefficient (*C*= 0.37 for animals on extensive pasture, *C*= 0.17 for animals on improved pastures and *C*= 0 for animals in feedlot and in pasture supplementation); *W* refers to the live weight of animals (kg) (eq. S7). *Q* refers to the number of animals in the herd (eq. S2).

$$\mathrm{NEl}_{s,m,t} = \mathrm{MK} \times (1.47 + 0.40 \times \mathrm{MF}) \times \mathrm{Q}_{c=1,s,m,t} \times \theta\mathrm{l}_t \qquad \text{(eq. S14)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *NEl* is the net energy for lactation (MJ day^{-1}); *MK* is the amount of milk produced ($\text{kg.animal}^{-1}.\text{day}^{-1}$) (Table 8); *MF* refers fat content of milk (%) (Table 8). For *c*= 1, *Q* is the number of cows in the herd (eq. S3); *θl* is the lactation constant (*θl*= 1 for the months when cows are lactating and *θl*= 0 for others).

$$\mathrm{NEp}_{s,m,t} = \mathrm{Q}_{c=1,s,m,t} \times 0.75 \times \mathrm{NEm}_{c\,=\,1,s,m,t} \times \theta\mathrm{p}_t \qquad \text{(eq. S15)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *Nep* is the net energy required for pregnancy (MJ day^{-1}); For *c*= 1, *Q* is the number of cows in the herd (eq. S3); For *c*= 1, *NEm* is the net energy required for cows maintenance (eq. S12). *θp* is the pregnant constant (*θp*= 1 for the months when cows are pregnant and *θp*= 0 for others).

$$\mathrm{NEg}_{c,s,m,t} = \left\{\begin{matrix} 4.18\times\left[\left(0.035 \times \mathrm{W}_{c,s,m,t}{}^{0.75} \times \mathrm{W}_{c,s,m,t}{}^{1.119}\right) + \mathrm{ADG}_{c,s,t}\right] \\ \times\ \mathrm{Q}_{c,s,m,t} \end{matrix}\right\} \qquad \text{(eq. S16)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *NEg* refers to net energy needed for growth (MJ day^{-1}); *W* refers to the live weight of animals (kg) (eq. S7); *ADG* denotes average daily gain ($\text{kg.animal}^{-1}.\text{day}^{-1}$); (Table 2, (eq. S6) and *Q* is the number of animals in the herd (eq. S2).

$$\mathrm{REM}_c = 0.298 + 0.00335 \times \mathrm{DE}_c \qquad \text{(eq. S17)}$$

where *c* is the animal category. *REM* is the ratio of net energy available in a diet for maintenance to digestible energy consumed (dimensionless); *DE* denotes digestible energy expressed as a percentage of gross energy (% GE) (Table 9).

$$\mathrm{REG_c} = -0.036 + 0.00535 \times \mathrm{DE_c} \qquad \text{(eq. S18)}$$

where *c* is the animal category. *REG* is the ratio of net energy available for growth in a diet to digestible energy consumed (dimensionless); DE denotes digestible energy expressed as a percentage of gross energy (% GE) (Table 9).

$$\mathrm{GE}_{c,s,m,t} = \left[\left(\frac{\mathrm{NEm}_{c,s,m,t} + \mathrm{NEa}_{c,s,m,t} + \mathrm{NEl}_{m,t} + \mathrm{NEp}_{s,m,t}}{\mathrm{REM_c}}\right) + \frac{\mathrm{NEg}_{c,s,m,t}}{\mathrm{REG_c}} \times {}^{100}\!/_{\mathrm{DE_c}} \times 30\right] \qquad \text{(eq. S19)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *GE* is the gross energy (MJ day^{-1}); *NEm* is the net energy required by the animal for maintenance (MJ day^{-1}) (eq. S12); *NEa* is the net energy for animal activity (MJ day^{-1}) (eq. S13); *NEl* is the net energy for lactation (MJ day^{-1}) (eq. S14); *Nep* is the net energy required for pregnancy (MJ day^{-1}) (eq. S15); *NEg* refers to net energy needed for growth (MJ day^{-1}) (eq. S16); *REM* is the ratio of net energy available in a maintenance diet for digestible energy consumed (dimensionless) (eq. S17); *REG* is the ratio of net energy available for growth in a diet to digestible energy consumed (dimensionless) (eq. S18); DE denotes digestible energy expressed as a percentage of gross energy (% GE) (Table 9). The factor 30 switches daily time steps to monthly time steps.

$$\mathrm{CH_4ent}_{s,m,t} = \sum_{c}\left(\mathrm{GE}_{c,s,m,t} \times \frac{\mathrm{Ym_c}}{100}\right) \times \frac{1}{55.65} \qquad \text{(eq. S20)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *CH$_4$ent* is the methane enteric emissions (kg); *GE* denotes the gross energy (MJ animal^{-1} day^{-1}) (eq. S19); *Ym* refers to methane conversion factor (%) (Table 9). The factor 55.65 is the methane energy content (MJ.kg CH$_4$$^{-1}$).

5.3.2 CH$_4$ emissions from manure

Methane emissions from manure are calculated according IPCC's tier 2 (Ipcc, 2006), as follow:

$$\mathrm{Vs}_{c,s,m,t} = \left[\mathrm{GE}_{c,s,m,t} \times \left(1 - \frac{\mathrm{DE_c}}{100}\right) + \left(\mathrm{UE} \times \mathrm{GE}_{c,s,m,t}\right)\right] \times \left[\left(\frac{1 - \mathrm{ASH}}{18.45}\right)\right] \qquad \text{(eq. S21)}$$

where s is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *V*s is the daily volatile solid excreted (kg dry matter animal^{-1} day^{-1}); *GE* denotes the gross energy (MJ animal^{-1} day^{-1}) (eq. S19); *DE* is the digestible energy expressed as a percentage of gross energy (% GE) (Table 9); *UE* is urinary energy expressed as fraction of GE (Table 8); ASH is the ash content of manure calculated as a fraction of the dry matter feed intake (Table 8).

$$\mathrm{Efman}_{c,s,m,t} = \mathrm{Vs}_{c,s,m,t} \times \mathrm{Bmax} \times 0.67 \times \frac{\mathrm{MCF}}{100} \times 30 \qquad \text{(eq. S22)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *Efman* is the methane emission factor of manure (kg CH_4.animal^{-1}); *V*s is the daily volatile solid excreted (kg dry matter animal^{-1} day^{-1}) (eq. S21); *Bmax* refers to maximum methane producing capacity for manure (m^3 CH_4 kg^{-1} of VS excreted) (Table 8).The factor 0.67 is used to convert m^3 CH_4 to kg CH_4; *MCF* is methane conversion factors for manure management system (%) (Table 8).

$$\mathrm{CH_4man}_{s,m,t} = \sum_{c} \mathrm{Efman}_{c,s,m,t} \times \mathrm{Q}_{c,s,m,t} \qquad \text{(eq. S23)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *CH_4man* refers to methane emissions from herd manure (kg); *Efman* denotes the methane emission factor of manure (kg CH_4.animal^{-1}) (eq. S22) and *Q* refers to the number of animals in the herd.

5.3.3 N_2O emissions from manure

Nitrous oxide emissions from manure are calculated according IPCC's tier 2 (Ipcc, 2006), as follow:

$$\mathrm{NEma}_c = \mathrm{REM}_c \times 18.45 \times \frac{\mathrm{DE}_c}{100} \qquad \text{(eq. S24)}$$

where *c* animal category. *NEma* is the net energy concentrate of diet (Mj.kg^{-1}); *DE* denotes digestible energy expressed as a percentage of gross energy (% GE).

For animals in growth stage, *DMI* is calculated as follow:

$$\mathrm{DMI}_{c,s,m,t} = \left[\frac{\left(0.2444 \times \mathrm{NEma}_c - 0.0111 \times \mathrm{NEma}_c^{\,2} - 0.472\right)}{\mathrm{NEma}_c}\right] \times \mathrm{W}_{c,s,m,t}^{\,0.75} \qquad \text{(eq. S25)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *DMI* is the dry matter intake (kg); *W* refers to the live weight of animals (kg) (eq. S7); *NEma* is the net energy concentrate of diet ($\mathrm{Mj.kg^{-1}}$) (eq. S24).

For *c*= 1 (cows) and *c*= 2 (bulls), *DMI* is calculated by (eq. S26).

$$\mathrm{DMI_{c,s,m,t}} = \mathrm{W_{c,s,m,t}}^{0.75} \times \left[\frac{\left(0.0119 \times \mathrm{NEma_c}^2 + 0.1938\right)}{\mathrm{NEma_c}}\right] \qquad \text{(eq. S26)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *W* refers to the live weight of animals (kg) (eq. S7); *NEma* is the net energy concentrate of diet ($\mathrm{Mj.kg^{-1}}$) (eq. S24).

$$\mathrm{NI_{c,s,m,t}} = \mathrm{DMI_{c,s,m,t}} \times \frac{\mathrm{CP_c}}{100} \times \frac{1}{6.25} \times \mathrm{Q_{c,s,m,t}} \times 30 \qquad \text{(eq. S27)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *DMI* is the dry matter intake (kg) ((eq. S25); (eq. S26)); CP is the protein content in diet of animals (%) (Table 9); *Q* refers to the number of animals in the herd (eq. S2).

$$\mathrm{Nex_{c,s,m,t}} = \mathrm{NI_{c,s,m,t}} - \left(\mathrm{Q_{(c=1,s,m,t)}} \times \mathrm{MK} \times \frac{\mathrm{CPM}}{100}\right) - 0.025 \times \mathrm{ADG_{c,s,t}} \qquad \text{(eq. S28)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *Nex* is the total N excretion from manure (kg); *NI* denotes the total N intake (kg) (eq. S27); *CPM* is the protein content in milk (%) (Table 8); For *c*= 1, *Q* is the number of cows in the herd (eq. S3); *MK* is the amount of milk produced ($\mathrm{kg.animal^{-1}.day^{-1}}$) (Table 8); *ADG* denotes average daily gain ($\mathrm{kg.animal^{-1}.day^{-1}}$) (Table 2, (eq. S6)). The ratio of N excreted in urine and dung were calculated by eq. S29 according Scholefield et al.(1991).

$$\mathrm{Nex\_d_{c,s,m,t}} = \frac{\mathrm{Nex_{c,s,m,t}}}{\left((1+1.2725)\times\frac{\mathrm{CP_c}}{6.25}\right) - 1.09} \qquad \text{(eq. S29)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *Nex_d* refers to N excretion in dung of animals (kg); *Nex* is the total N excretion from manure (kg) (eq. S28); CP is the protein content in animal diet (%) (Table 9). The factor 6.25 converts amount of protein to amount of N.

$$\mathrm{Nex\_u_{c,s,m,t}} = \mathrm{Nex_{c,s,m,t}} - \mathrm{Nex\_d_{c,s,m,t}} \qquad \text{(eq. S30)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *Nex_u* refers to N excretion in urine of animals (kg); *Nex* is the total N excretion from manure (kg) (eq. S28). *Nex_d* refers to N excretion in dung of animals (kg) (eq. S29).

$$\mathrm{N_2Omp\_d}_{\mathrm{s,m,t}} = \sum_{\mathrm{c}} \left(\mathrm{Nex\_d}_{\mathrm{c,s,m,t}} \times \mathrm{EFd} + \mathrm{Nex\_u}_{\mathrm{c,s,m,t}} \times \mathrm{EF_u} \times \frac{44}{28}\right) \qquad \text{(eq. S31)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *N$_2$Omp_d* is the direct N_2O emissions from the manure of animals on pasture (kg); *Nex_d* refers to N excretion in dung of animals (kg) (eq. S29); *Nex_u* is to N excretion in urine of animals (kg) (eq. S30); *EFd* is the emission factor for direct N_2O emissions from dung (kg N_2O_N.kg N excreted^{-1}) (Table 8) and *EFu* is the emission factor for direct N_2O emissions from urine (kg N_2O_N.kg N excreted^{-1}) (Table 8); The factor 44/28 converts N_2O_N to N_2O emissions.

$$\mathrm{N_2Omp\_i}_{\mathrm{s,m,t}} = \sum_{c} \left[\begin{matrix} \left(\mathrm{Nex}_{\mathrm{c,s,m,t}} \times \mathrm{FR\_mpvol} \times \mathrm{EF\_vol}\right) + \\ \left(\mathrm{Nex}_{\mathrm{c,s,m,t}} \times \mathrm{FR\_lch} \times \mathrm{EF\_lch} \times {}^{44}/_{28}\right) \end{matrix}\right] \qquad \text{(eq. S32)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *N$_2$Omp_i* is the indirect N_2O emissions from the manure of animals on pasture (kg); *Nex* is the total N excretion from manure (kg) (eq. S28); *FR_mpvol* denotes the fraction of N excreted on pastures that volatilizes (NH_3–N + NO_x–N. kg N Excreted^{-1}) (Table 8); *FR_lch* is the fraction of N excreted that leaches (kg NH_3–N + NO_x–N. kg N Excreted^{-1}) (Table 8). *EF_vol* is the emission factor of N_2O from volatized N (kg N_2O–N (kg NH_3–N + NO_X–N volatilized)$^{-1}$) (Table 8); *EF_lch* is the emission factor for N_2O emissions from N leaching and runoff, kg N_2O–N (kg N leached and runoff)$^{-1}$ (Table 8). The factor 44/28 converts N_2O_N to N_2O emissions.

$$\mathrm{N_2Omp}_{\mathrm{s,m,t}} = \mathrm{N_2Omp\_d}_{\mathrm{s,m,t}} + \mathrm{N_2Omp\_i}_{\mathrm{s,m,t}} \qquad \text{(eq. S33)}$$

where *s* is the management scenario, *m* municipality, *t* time (month). *N$_2$Omp* is the nitrous oxide emissions from manure of the animals on pasture regime (kg); *N$_2$Omp_d* is the direct N_2O emissions from the manure of animals on pasture (kg) (eq. S31) and *N$_2$Omp_i* is the indirect N_2O emissions from the manure of animals on pasture (kg) (eq. S32).

$$\mathrm{N_2Omc\_d}_{\mathrm{s,m,t}} = \mathrm{Nex}_{\mathrm{c\,=\,10,s,m,t}} \times \mathrm{Q}_{\mathrm{c\,=\,10,\,s,m,t}} \times \mathrm{EFm} \times \frac{44}{28} \qquad \text{(eq. S34)}$$

where *s* is the management scenario, *m* municipality, *t* time (month) and *c* animal category. *N₂Omc_d* is the direct nitrous oxide emissions from manure of the animals under feedlot (kg); For *c*= 10, *Nex* is the total N excretion from manure of animals under feedlot (kg) (eq. S28). For *c*= 10, *Q* is the number of animals under feedlot; *EFm* is the direct N_2O emission factor for manure management (Kg N_2O-N kg N^{-1}) (Table 8); The factor 44/28 converts N_2O_N to N_2O emissions.

$$N_2Omc\_i_{s,m,t} = \begin{bmatrix} Nex_{c\,=\,10,s,m,t} \times Q_{c\,=\,10,s,m,t} \times \\ (FR\_mcvol \times EF\_vol + FR\_lch \times EF\_lch) \times {}^{44}/_{28} \end{bmatrix} \qquad \text{(eq. S35)}$$

where *s* is the management scenario, *m* municipality, *t* time (month). *N₂Omc_i* is the indirect nitrous oxide emissions from manure of the animals under feedlot (kg); For *c*= 10, *Nex* is the total N excretion from manure of animals under feedlot (kg) (eq. S28); For *c*= 10, *Q* is the number of animals under feedlot; *FR_mcvol* denotes the fraction of N from manure that volatilizes as NH_3 and NOx (kg NH_3–N + NO_x–N. kg N Excreted^{-1}) (Table 8); *EF_vol* is the emission factor for N_2O from N that volatilize (kg N_2O–N (kg NH_3–N + NO_X–N volatilized)$^{-1}$) (Table 8); *FR_lch* denotes the fraction of N from manure that leaches (kg N_2O_N. kg N excreted^{-1}) (Table 8). *EF_lch* denotes the emission factor for N_2O from N that leaches (kg N_2O–N (kg N leaching/runoff)$^{-1}$) (Table 8). The factor 44/28 converts from N_2O_N to N_2O emissions.

$$N_2Omc_{s,m,t} = N_2Omc\_d_{s,m,t} + N_2Omc\_i_{s,m,t} \qquad \text{(eq. S36)}$$

where *s* is the management scenario, *m* municipality, *t* time (month). *N₂Omc* is the nitrous oxide emissions from manure of the animals under feedlot (kg); *N₂Omc_d* is the direct nitrous oxide emissions from manure of the animals under feedlot (kg) (eq. S34) and *N₂Omc_i* is the indirect nitrous oxide emissions from manure of the animals under feedlot (kg) (eq. S35).

$$N_2Oman_{s,m,t}=N_2Omp_{s,m,t}+N_2Omc_{s,m,t} \qquad \text{(eq. S37)}$$

where *s* is the management scenario, *m* municipality, *t* time (month). *N₂Oman* is the total nitrous oxide emissions from manure of the herd (kg); *N₂Omp* is the nitrous oxide emissions from manure of the animals on pasture regime (kg) (eq. S33) and *N₂Omc* is the nitrous oxide emissions from manure of the animals under feedlot (kg) (eq. S36).

5.3.4 N_2O emissions from fertilizer

Nitrous oxide emissions from synthetic fertilizer are calculated as proposed by IPCC’s tier 2 (Ipcc, 2006). In Brazil, urea is the main source of N fertilizer (Alves, 2014), which presents larger losses of N due to volatilization, especially when applied onto soil surface. We consider the adaptation proposed by Alves (Alves, 2014), wherein the N_2O emission factor from N fertilizer applied as urea is 0.30, while for N fertilizer applied as other sources is 0.1 (Ipcc, 2006). Here we assume that 50% of N fertilizer comes from urea.

$$N_2Of\_d_{s,m,t} = Pa\_ref_{s,m,t} \times Nfert_{s,m,t} \times EFfertd \times \frac{44}{28} \qquad \text{(eq. S38)}$$

where *s* is the management scenario, *m* municipality, *t* time (month). *N_2Of_d* is the direct N_2O emission from synthetic fertilizer applied in soil (kg); *Pa_ref* refers to pasture area restored (ha); *Nfert* is the amount of N synthetic fertilizer applied in the soil (kg.ha^{-1}) (Table 8); *EFfertd* refers to direct N_2O emission factor from N synthetic fertilizer applied in soil (kg N_2O_N kg N^{-1}) (Table 8). The factor 44/28 converts N_2O_N to N_2O emissions.

$$N_2Of\_i_{s,m,t} = \left\{ Pa\_ref_{s,m,t} \times Nfert_{s,m,t} \times \left[\begin{matrix} \left(\frac{FR\_fvol1+FR\_fvol2}{2}\right) \times EF_{vol} \\ +FR\_lch \times EF\_lch \end{matrix} \right] \right\} \times {}^{44}/_{28} \qquad \text{(eq. S39)}$$

where *s* is the management scenario, *m* municipality, *t* time (month).); *N_2Of_i* is the indirect N_2O emission from synthetic fertilizer applied in soil (kg); *Pa_ref* refers to pasture area restored (ha); *Nfert* is the amount of N synthetic fertilizer applied in soil (kg.ha^{-1}) (Table 8); *FR_fvol1* denotes the fraction of N synthetic applied in soil as fertilizer in urea that volatilize (kg NH_3–N + NO_x–N. kg N applied^{-1}) (Table 8); *FR_fvol2* denotes the fraction of N synthetic applied in soil as fertilizer in other sources that volatilize (kg NH_3–N + NO_x–N. kg N applied^{-1}) (Table 8). *EF_vol* is the emission factor of N_2O from volatized N (kg N_2O–N (kg NH_3–N + NO_X–N volatilized)$^{-1}$). *FR_lch* denotes the fraction of N synthetic applied in soil as fertilizer that leaches (kg N_2O_N. kg N applied^{-1}) (Table 8). *EF_lch* denotes the emission factor for N_2O from N that leaches (kg N_2O–N (kg N leaching/runoff)$^{-1}$) (Table 8). The factor 44/28 converts N_2O_N to N_2O emissions.

$$N_2Ofert_{s,m,t} = \left(N_2Of\_d_{s,m,t} + N_2Of\_i_{s,m,t}\right) \times \theta f_t \qquad \text{(eq. S40)}$$

where *s* is the management scenario, *m* municipality, *t* time (month). *N_2Ofert* refers to total N_2O emissions from synthetic fertilizer (kg). *N_2Of_d* is the direct N_2O emission from synthetic fertilizer applied in soil (kg) (eq. S38); *N_2Of_i* is the indirect N_2O emission from synthetic fertilizer applied in soil (kg) (eq. S39); *θf* is the fertilizer constant (*θf*= 1 for the month when fertilizer application take place (it happens once every 12 months) and *θf*= 0 for others).

5.3.5 CO_2 emissions from fertilizer

The CO_2 emissions from limestone and urea applied in soil is calculated as proposed by IPCC's Tier 1 (Ipcc, 2006) as follow:

$$\mathrm{CO_2u_{s,m,t}}=\mathrm{Pa\_ref_{s,m,t}}\times\frac{\mathrm{Nfert_{s,m,t}}}{2}\times\mathrm{EFCO_2u}\times\frac{44}{12} \qquad \text{(eq. S41)}$$

where *s* is the management scenario, *m* municipality, *t* time (month). CO_2u refers to CO_2 emissions from N synthetic fertilizer applied in soil as urea (kg); *Pa_ref* refers to pasture area restored (ha); *Nfert* is the amount of N synthetic fertilizer applied in soil (kg.ha^{-1}) (Table 8); $EFCO_2u$ is the CO_2 emission factor for urea applied as N fertilizer (kgC.kg urea^{-1}) (Table 8). The factor 44/12 converts from CO_2_C to CO_2 emissions.

$$\mathrm{CO_2Lm_{s,m,t}}=\begin{bmatrix}\mathrm{C\_Lm_{s,m,t}}\times\left(\mathrm{Pa\_ref_{s,m,t}}-\mathrm{Pa\_ref_{s,m,t-1}}\right)\times\mathrm{EF\_Lm}\\ \times{}^{44}/_{12}\times\theta\mathrm{c_t}\end{bmatrix} \qquad \text{(eq. S42)}$$

where s is the management scenario, *m* municipality, *t* time (month). CO_2Lm refers to CO_2 emission from limestone applied in soil (kg); *C_Lm* is the amount of limestone applied in soil (kg ha^{-1}) (Table 8); *Pa_ref* refers to pasture area restored (ha); *EF_Lm* denotes the limestone emission factor (kg C.kg de limestone^{-1}) (Table 8). The factor 44/12 converts m CO_2_C to CO_2 emissions. *θc* is the limestone constant (*θc*= 1 for the month when limestone is applied (it happens once every 12 months) and *θc*= 0 for others).

5.3.6 CO_2 fixation

The CO_2 fixation in organic carbon in soil of improved pasture is calculated as follow:

$$\mathrm{CO_2\_soil_{s,m,t}}=\mathrm{Pa\_ref_{s,m,t}}\times\frac{\mathrm{SOCr}}{12}\times\frac{44}{12} \qquad \text{(eq. S43)}$$

where *s* is the management scenario, *m* municipality, *t* time (month). CO_2_soil corresponds to carbon fixation by improved pastures (kg); *Pa_ref* refers to pasture area restored (ha); *SOCr* is the rate of C sequestration (kg C.ha^{-1}) (Supplementary Methods).

5.3.7 GHG budget

$$CO_2e_{s,m,t}=\begin{bmatrix}(CH_4ent+CH_4man)_{s,m,t}\times GWP_1+(N_2Oman+N_2Ofert)_{s,m,t}\\ \times GWP_2+CO_2Lm_{s,m,t}+CO_2u_{s,m,t}-CO_2soil_{s,m,t}\end{bmatrix} \quad \text{(eq. S44)}$$

where *s* is the management scenario, *m* municipality, *t* time (month). CO_2e is the GHG budget (kg CO_2e); CH_4ent is the methane enteric emissions (kg) (eq. S20); CH_4man refers to methane emissions from herd manure (kg) (eq. S23); N_2Oman is the total nitrous oxide emissions from manure of the herd (kg) (eq. S37); N_2Ofert refers to total N_2O emissions from synthetic fertilizer (kg) (eq. S40); CO_2Lm refers to CO_2 emission from limestone applied in soil (kg) (eq. S42); CO_2u refers to CO_2 emissions from N synthetic fertilizer applied in soil as urea (kg) (eq. S41); CO_2_soil is the carbon fixation by improved pastures (kg) (eq. S43). GWP_1 e GWP_2 is the global warming potential for methane and N_2O, 28 and 265 respectively (Myhre *et al.*, 2013).

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