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LETTER

Large-scale pasture restoration may not be the best option to reduce greenhouse gas emissions in Brazil

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Abstract

Cattle ranching accounts for 44% of the greenhouse gas (GHG) emissions from the land use sector in Brazil. In response, Brazil has proposed a massive pasture restoration program that aspires to make ranching more competitive while at the same time reducing associated GHG emissions. Pasture restoration, however, is only one of several intensification options that could be employed to achieve these goals. Here we analyze potential production, economic return and GHG emissions from an intensification strategy based mainly on pasture restoration and compare its productive, economic and GHG emissions performances with intensification options more focused on supplemental feeding (grain-feed supplementation of grazing animals and animal finishing in feedlots). To this end, we developed a multi-sectoral, deterministic simulation model of the ranching system and applied it to Mato Grosso state, the largest producer and earliest adopter of intensive production. To account for GHG emissions, we performed a life cycle analysis of a complete beef production cycle. Our results show that an intensification strategy focused more heavily on pasture restoration does reduce GHG emissions but produces the least favorable economic and GHG emissions outcomes when compared with a range of supplemental feeding alternatives. In view of these results, Brazil should seek a more diversified strategies for cattle intensification in its climate mitigation policy.

1. Introduction

Cattle ranching is said to be responsible for 44% of Brazil's greenhouse gas (GHG) emissions from the land use sector (SEEG 2016). The cattle herd and attributable GHG emissions are projected to increase as the demand for beef increases both nationally and internationally (Tilman *et al* 2011, MAPA 2018). Although Brazil's beef industry is the world's second largest producer and largest exporter by volume, it continues to be dominated by lower productivity and product value compared to its main competitors. In 2015, for example, Brazil produced 9.2 million tons (Mt) of beef from 215 million head (Mhd) and generated a gross product value of US$ 22 billion, while the USA produced 10.8 Mt of beef from a herd of 89 million and generated US$ 105 billion (MAPA 2016, USDA, 2016a, 2016b, IBGE 2018). This difference in productivity and value has, in part, led to the belief that intensifying cattle ranching in Brazil may represent a potentially low cost option to spare land for agricultural production and mitigate GHG emissions, while increasing profits to ranchers and meeting the rising demand for beef (de Gouvelo *et al* 2010, Bustamante *et al* 2012, Cohn *et al* 2014).

To take advantage of this opportunity, Brazil has proposed that large-scale pasture restoration will be a cornerstone of its Nationally Appropriate Mitigation Measures and its Nationally Determined Contribution (NDC) to the Paris agreement. Pasture restoration technology and investment range from simple fertilization to mechanical interventions (e.g. plowing and replanting). Here we assume restoration to require the full complement of seeds, fertilizer, lime, and mechanized operations. The proposed NDC target includes the restoration of 15 Mha of pasture by 2030 in addition to the 15 Mha already proposed by Brazil's Low Carbon Agriculture Plan (Brasil 2012, Brasil 2015), aiming for a total restoration target of 30 Mha. The expected emission reduction from this commitment relies on the ability of restored pasture to sequester carbon in the soil, while at the same time improving roughage digestibility to reduce enteric methane emissions (Maia *et al* 2009, Braz *et al* 2013, Herrero *et al* 2016). In addition, more intensive systems can reduce GHG emissions per unit of beef by shortening the time to slaughter (Cardoso *et al* 2016).

Pasture restoration, however, is only one option in an array of intensification approaches. Alternative and/or complementary strategies include additional nutrients for calves in the suckling phase (Creep feeding), grain-feed supplements for grazing animals, animal finishing in confinements or feedlots, and animal finishing in semi-confinement (i.e. grazing animals receiving a high protein-energetic diet in the fattening phase), all of which aim to accelerate the weight gain of individual animals (Thornton and Herrero 2010, Barbosa *et al* 2015). Although market forces are pushing intensification towards confined feeding operations (Rabobank 2014), government interventions emphasize a more pasture-based mode of intensification (Brasil 2012, Brasil 2015). A particular challenge for policy makers, therefore, is to determine a more optimal mix of strategies that could meet future demands for beef, lower GHG emissions and avoid pasture expansion into native vegetation areas in a context of increasing economic competition.

The Brazilian livestock sector still has many opportunities to increase the use of intensification strategies. Although Mato Grosso, Brazil's largest beef producing state, had increased the number of animals in feedlots to about 0.89 Mhd in 2012 (figure S1 is available online at stacks.iop.org/ERL/14/125009/mmedia), accounting for almost a quarter of total of confined animals in Brazil (ANUALPEC 2015), the state continues to rely mostly on extensive ranching with low pasture stocking density rates (Barbosa *et al* 2015). We estimate that approximately 80% of municipalities in Mato Grosso, 90% of which comprise of pasturelands, present some level of degradation, of which ≈8 Mha could be characterized as having high levels of degradation (Dias-Filho 2014) (table S1). Some researchers fear that the increasing beef demand in Brazil, which is expected to grow from 9.9 Mt of carcass weight equivalent (CWE) in 2018 to 12.1 Mt CWE in 2028 (MAPA 2018), may occur at the cost of native vegetation losses (Arima *et al* 2011). In Mato Grosso, for example, complex land use dynamics related to livestock and agricultural production as well as land speculation (Merry and Soares-Filho 2017, Miranda *et al* 2019) may drive native vegetation losses in adjacent areas (Barona *et al* 2010). At the same time, the adequate infrastructure and attractive production conditions in Mato Grosso (Barbosa *et al* 2015) provide great potential for intensification of the livestock sector that may reduce requirements for new land.

A number of studies have analyzed cattle ranching intensification with a focus on separate productive, economic or environmental aspects under quite specific conditions (Strassburg *et al* 2014, Cardoso *et al* 2016, de Oliveira Silva *et al* 2016, de Oliveira Silva *et al* 2017). At the same time, however, these studies remain unclear about the economic and environmental effects of different strategy mixes for cattle intensification in a geographically varying regional context. Addressing this research gap requires taking into account that technology adoption and production strategies may vary across space, time, and landowner characteristics. Climate and terrain aptitude, property size, rancher background, local infrastructure, distance to markets and input and output prices will all determine if and where intensification modes may succeed.

Here we analyze the potential production, economic return and GHG emissions from three intensification strategy mixes with varying emphasis on pasture restoration, creep feeding and feedlot finishing for the period 2012–2030. To this end, we developed a multi-sectoral deterministic model (SIMPEC) to represent a beef production cycle and its associated impacts on economic outcomes and GHG emissions (supplementary material note) and applied it to the state of Mato Grosso. The remainder of this paper provides a description of the analytical framework, outlines possible intensification scenarios, and then discusses the results of the simulation runs. More information and specific details are provided in the supplementary material.

2. Methods

2.1. General approach

Our analysis of the potential production, economic return and GHG emissions via different pathways involves four scenarios for the livestock sector in Mato Grosso: a baseline scenario (BASE) and three intensification strategy mixes that emphasize pasture restoration (MIX-PAST), feedlot finishing (MIX-FEED) and creep feeding plus feedlot finishing (MIX-FEED+). The analysis of these scenarios builds on a model for the simulation of livestock production systems: SIMPEC model (Portuguese acronym: *Simulação de Sistemas de Produção da Pecuária de Corte*). The SIMPEC model contains three components or modules (figure 1). The herd module simulates the dynamics of a complete beef production cycle at selected spatial units. This production cycle occurs in a closed domain, which means that factors like buying and selling land are exogenous to the simulation. The economic module calculates the financial costs and returns of adopting the livestock management

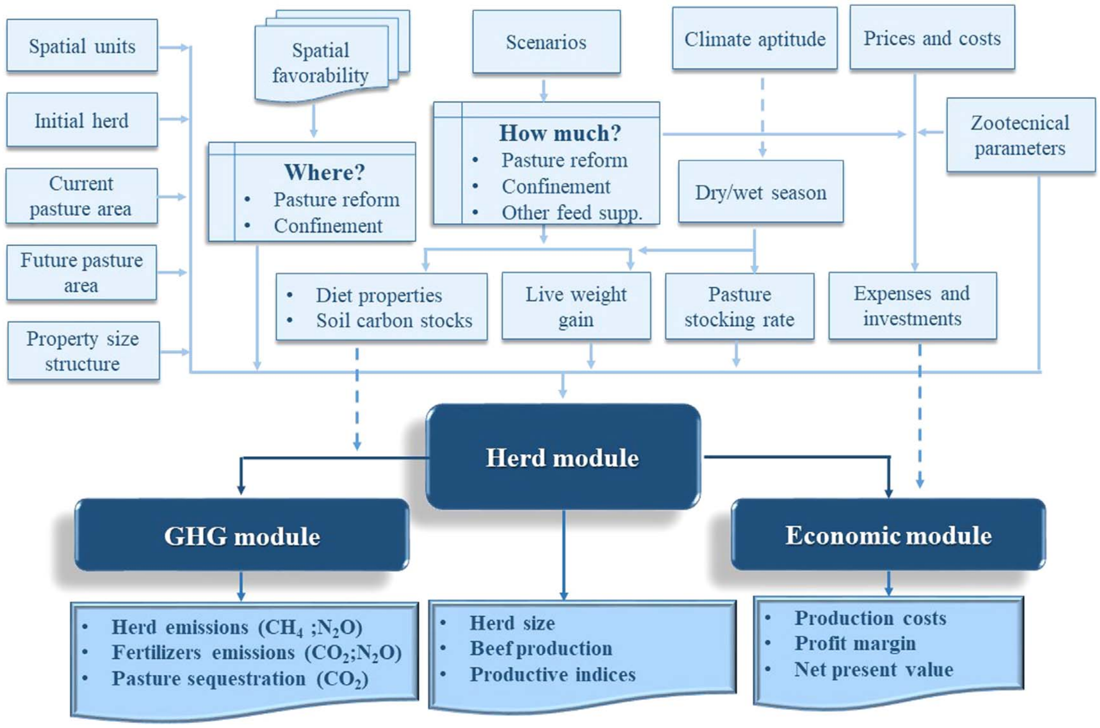

Figure 1. Overall flowchart of the SimPec model, depicting main inputs (light blue), outputs (intermediate blue), and processing modules (dark blue).

practices that are characteristic of each scenario. The GHG module, finally, calculates the GHG emissions that are associated with each scenario. Section 2.2 elaborates on the input parameters for these modules, while section 2.3 discusses the scenarios.

2.2. Input parameter settings

In the herd module, the SIMPEC model simulates the dynamics of a representative ranching system on monthly time steps from 2012 to 2030 for each municipality in Mato Grosso (equations S1–S7—herd dynamics module in supplementary material). This simulation accounts for the municipality's pasture stocking density rate (i.e. animal units (AU) per hectare; 1 AU = 450 kg of live weight), pasture area, and property size distribution in 2012. As of 2012, roughly 0.89 Mhd are being finished in feedlots, while 0.33 Mhd are finished on semi-confinements (ANUALPEC 2015). The technical coefficients (table 1) adopted for extensive systems are typical for cattle ranching in central-west Brazil (Corrêa *et al* 2006), while those for improved systems are based on secondary information and expert consultation.

Feedlot and semi-confinement finishing occurs preferentially during the dry season. In feedlots, the animals receive a diet based on grains, silage and a mineral mix, while the supplementary feeding in semi-confinement consists mainly of grains and mineral mix. For specific modeled scenarios, we also assume the adoption of creep feeding. For an improved economic and development context, SIMPEC takes into account local agricultural aptitude, current and future regional logistics along with underlying scenarios of land use change. The amount and location of future pasture areas, agricultural and forest plantation expansion as well as forest restoration to comply with the Brazilian Forest Code in low productive pasture areas are incorporated using previously published results (Soares-Filho *et al* 2016, Rochedo *et al* 2018) (table S2).

While the BASE scenario assumes that the current upward deforestation trend will continue into the future (Soares-Filho *et al* 2016), the three intensification scenarios assume lower rates of deforestation (Rochedo *et al* 2018) needed to attain the targets of the NDC and remain under the Forest Reference Levels Emissions for the Cerrado and the Amazon biomes (MMA and MCTI 2014, MMA 2017). Therefore, the intensification scenarios develop under a strong environmental governance (Rochedo *et al* 2018) that includes the full implementation of Brazilian policies to achieve its NDC targets (Brasil 2015). Under these circumstances, our study assesses the possible pathways to achieve beef intensification as a component of the ABC Program—Brazil's main strategy for sustainable low-carbon agricultural development. Although pasturelands still expand in detriment of native vegetation, with commensurate GHG emissions (tables S2 and S3), this is much less in a strong governance scenario assumed for the intensification analysis (Rochedo *et al* 2018). Nevertheless, the total ranching area in Mato Grosso reduces due to agricultural land

Table 1. Technical coefficients for cattle ranching systems at the present and under our simulation scenarios[a].

per scenario	**Current**[b]	**BASE**	**MIX-PAST**	**MIX-FEED**	**MIX-FEED+**
Herd ratio (bull/cows)	1:25	1:35	1:35	1:35	1:35
Calving rate (%)	60	70	80	80	80
Mortality <12 months (%)	5.0	4.0	3.0	3.0	3.0
Mortality >12 months (%)	2.0	1.5	1.0	1.0	1.0
Weight calves at weaning (kg)	160	170	180	180	220[c]
Weight heifers at weaning (kg)[d]	145	160	170	170	210[c]
Average growth rate of steers in semi-confinement (% yr^{-1})		3.0	3.0	3.0	3.0
Average growth rate of steers in feedlot (% yr^{-1})		3.6	3.6	6.7	6.7
Average area restored annually (ha × 1000)		156	278	216	195
for all scenarios					
			MALE		*FEMALE*
Weight at birth (kg)			30		30
Weight adult animal (kg) (cows and bulls)			550		420
Weaning (months)			7		7
ADG—extensive pasture dry season (kg d^{-1})[b,c,e]			0.10		0.08
ADG—extensive pasture wet season (kg d^{-1})[b,c,e]			0.50		0.38
ADG—improved pasture dry season (kg d^{-1})[c,e]			0.20		0.15
ADG—improved pasture wet season (kg d^{-1})[c,e]			0.60		0.40
ADG—semi-confinement (kg d^{-1})[f]			0.85		—
ADG—feedlot (kg d^{-1})[g]			1.5		—
Initial weight—feedlot and semi-confinement (kg)			360		—
SW—pasture (kg)[b,c]			490		390
SW—feedlot and semi-confinement (kg)			510		—
CDP—pasture (%)[c]			52		49
CDP—semi-confinement (%)[c]			53		—
CDP—feedlot (%)[g]			54		—
CDP—discarded animals (cows and bulls) (%)[c]			50		49

Note. ADG = average daily weight gain; SW = Slaughter weight; CDP = Carcass dressing percentage.

[a] In the projected scenarios, these values are applied to areas appropriate for intensification (in properties larger than 500 ha). For other areas, we keep constant the current technical coefficients. We assume the transition of technical coefficients occurring gradually within an initial time period of 10 years.

[b] Technical coefficients for a typical extensive cattle ranching system in the Brazilian Midwest (Corrêa *et al* 2006).

[c] In the MIX-FEED+ scenario, we assume the use of creep feeding, hence calves are weaned 40 kg heavier by the consumption of 1% of body weight of protein-energy-mineral supplemented during 3 months (Carvalho *et al* 2003). Creep feeding provides additional nutrients for calves in the suckling phase. The composition of creep feeding diet is in table S6.

[d] Values defined based on experts' consultation.

[e] We assume that the animals on pasture receive protein-mineral supplement in the dry season only and mineral supplement in wet season only. Table S6 shows the consumption and composition of each supplement feeding. More information about the definition of dry and wet season are provided in the supplementary methods.

[f] ADG supported by the supplement consumption of 1.4% of body weight under semi-confinement (Barbosa et al., 2016). Feeding composition of these animals is described in table S6.

[g] Values based on Oliveira and Millen (2014). ADG is supported by the consumption of 2.3% of body weight of animals in feedlot (table S6).

expansion over degraded pasturelands as projected by Rochedo *et al* (2018), plus additional cropland needed to feed the herd under the different intensification strategies (tables S2 and S4). To this end, we assume that all additional feeding will come from mostly soy-corn (92% of the latter) grown as single crop (table S4). This is a conservative approach given that 70% of corn in Brazil is already harvested as a second crop (mostly in soy-corn double cropping systems) and this figure is expected to rise by 2030 (MAPA 2018).

For each scenario, all pastures are initially included in a low productive category (extensive category) with varying stock density according to municipal data for the year of 2012 (figure 3). Under each scenario, the model restores pastures in fixed annual rates. The location of restored pasture takes into account the regional potential for intensification (Barbosa *et al* 2015). We define the carrying capacity of restored pasture (figure S2) using estimates of fodder grass herbage accumulation (Strassburg *et al* 2014). Intensification in our model takes place only in properties equal or larger than 500 ha due to scale of production needed to pay back investments. This is equivalent to 19 Mha or 78% of pasturelands in Mato Grosso (figure S3). Nonetheless, all pasture and outputs within a municipality are considered when computing total production and average productivity under each modeled scenario (see section 2.3). Initial feedlot capacity is disaggregated by municipality using regional data (IMEA 2012) and increases at selected rates depending on the municipality's aptitude for intensification (Barbosa *et al* 2015).

In the economic module, the model uses revenues, investments and operational costs to calculate net returns (equations S8–S11—economic module in supplementary material). Revenues are contingent on beef production, carcass dressing percentage, and local prices (figure S4). Investment costs include both pasture restoration and feedlot installation. Since our model treats the cattle production system as a closed domain, wherein there is no entry or exit of actors, we do not include the investment needed in setting up a ranch, such as land acquisition and other infrastructure, nor revenues from selling the herd and land to go out of business. Operational costs vary as a function of property size and management system (table S5). Returns to production are calculated as net present value (NPV) using an annual discount rate of 8.5% over the 18 years of the simulation period.

To estimate GHG emissions, we adopt a life cycle assessment approach, covering the full life cycle of the herd. We account for CH_4 from enteric fermentation (except suckling calves) and manure, N_2O from manure and fertilizer utilization, and CO_2 from urea and lime application (equations S12–S44—GHG module in supplementary material). We also account for CO_2 emissions from production, manufacture and transport of animal feeds, fuels, fertilizers, pesticides and other agrochemicals and from the manufacture of equipment and machinery used in the production systems (see methods in Cardoso *et al* 2016). Herd emission and fertilizer coefficients come from IPCC tier 2 and 1 estimates, respectively. Emissions from land use change to accommodate the additional cropland demand for feedstuff and carbon sequestration from restored pasture are estimated comparing C stocks after land use and/or management change relative to the carbon stock in a reference condition (IPCC 2003) (supplementary methods).

Because there is no consensus about the time for soils to return to equilibrium, we assume that SOC (Soil organic carbon) comes to an equilibrium after ≈20 years of land use/management change (IPCC 2006). As the degraded pastures in Mato Grosso are in general older than 20 years (MapBiomas 2018), restoration occurs without further losses of carbon.

Finally, we do not include biomass gain due to increased pasture yields, because pasture restoration also entails biomass losses from eradicated regrowth that often populates the so-called 'degraded pastures', which in many cases are larger than biomass gain in forage grasses (Wandelli and Fearnside 2015). 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 (Myhre *et al* 2013).

2.3. Intensification scenarios

We model one business-as-usual (BASE) and three intensification scenarios (MIX-PAST, MIX-FEED and MIX-FEED+). The BASE scenario builds on increasing cattle productivity between 1996 and 2012, which are projected into the future and serve as a baseline scenario. This scenario holds constant the historical parameters for herd growing (which will demand a pasture restoration of 156 000 hectares), feedlot finishing (growth rates of 3.6% per year) and weaning weight (160–170 kg) (table 1). In addition, this scenario does not consider meeting any demand target in the future. The three scenarios for different intensification strategy mixes (MIX-PAST, MIX-FEED and MIX-FEED+) are market driven intensification approaches, designed to meet a planned target of beef production for Mato Grosso of 2.0 Mt CWE in Mato Grosso by 2030. This target is based on the continuation of the annual growth rate for Brazil between 2015 and 2025, while assuming that Mato Grosso continues its average share in total production between 2009 and 2017 (table S7).

The MIX-PAST, MIX-FEED and MIX-FEED+ scenarios maintain the intensification strategy mix in the BASE, but adopts different emphases on one or more components. As the MIX-PAST scenario focuses primarily on pasture restoration, the parameters for feedlot and semi-confinement finishing are held constant, while the SIMPEC model is run for various levels of pasture restoration until arriving at a production level that would meet the demand of 2 Mt CWE. The same approach is used for the MIX-FEED and MIX-FEED+ scenarios, but with different emphases for feedlot finishing and creep feeding. In the MIX-FEED scenario, the feedlot finishing parameter (annual growth rate) is raised to 6.7%. The same feedlot finishing parameter used for the MIX-FEED + scenario, but with additional use of creep feeding, which increases the weaning weight from 170–180 to 210–220 kg.

Our study does not consider integrated systems where pasture is rotated with crops, because in this case beef production is typically a secondary product of intensive crop farming. Although beef intensification was proposed as a land sparing strategy (Phalan *et al* 2016), here we also assume that, based on evidence from Koch *et al* (2019), intensification is induced by conservation policies that shift investments from deforestation and land speculation (Miranda *et al* 2019) to capital investments in more profitable ranching practices that avoid illegality (Merry and Soares-Filho 2017), hence with no indirect impact (leakage) in land use changes (Richards *et al* 2014).

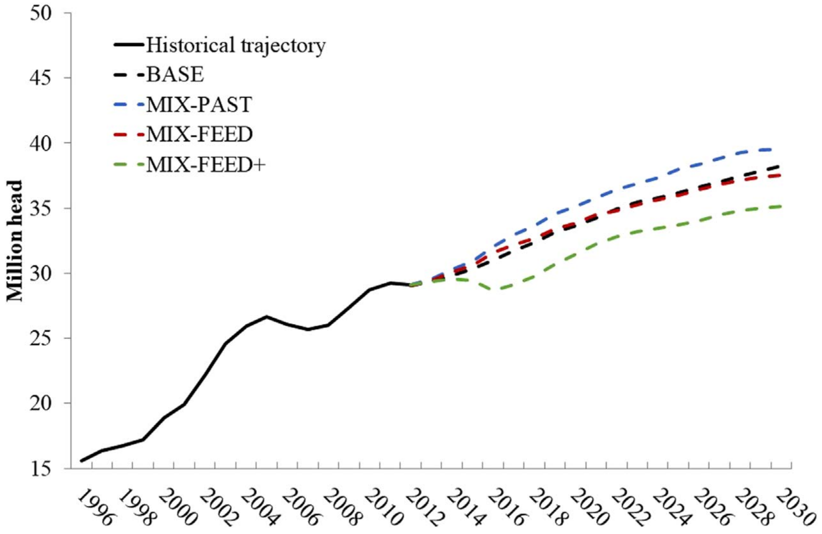

Figure 2. Herd's growth from 1996 to 2012 and under modeled scenarios.

3. Results

Here we describe some key results from the simulation runs. These include herd size and productivity; investments and economic returns; GHG emissions and the overall GHG budget.

3.1. Herd size and productivity

In the baseline scenario (BASE), the total herd in Mato Grosso will grow at a mean annual rate of 1.5%, reaching a total of 38 Mhd (figure 2) and a stock density of 0.90 AU—animal units (1 AU = 450 kg live weigh)—per hectare (0.8% yearly growth) produced on 28 Mha of pasture by 2030 (table 2). Even under this scenario, at least 2.8 Mha of pastures will need to be restored to accommodate the future herd (table 2). Steers finished in feedlots increase by 17% to a total of 23% of slaughtered animals, and those finished in semi-confinement will compose 8% of the slaughtered animals (figures S5, S6). Although, average productivity per hectare in intensified systems will increase annually by 2%, a future output beef production of 1.8 Mt under this scenario will be below the expected contribution of Mato Grosso to meet the national production target (table 2).

In order for the beef sector to meet the future planned production of 2.0 Mt—the share of Mato Grosso rated from the national target (scenarios MIX-PAST, MIX-FEED and MIX-FEED+ scenarios)—, the development scenario that focused more heavily on pasture restoration (MIX-PAST) requires the restoration of 5.0 Mha of the total 25.1 Mha of pastures by 2030 (table 2). Stock density in intensified systems will grow at a mean annual rate of 2.3%, reaching 1.15 AU ha^{-1} by 2030 (table 2). The number of steers finished in feedlot and pasture with supplemental feeding will steadily increase alongside the reduction of the slaughter age (figures S5, S6). These improvements will enable pasture productivity (measured in kg of CWE ha^{-1}) to increase by 107%. As a result, the herd will grow to 39.4 Mhd (figure 2). In the MIX-FEED scenario, where more investment and capacity is developed in feedlot finishing, this same level of production would be met with a herd of 37.5 Mhd on 25.0 Mha of pasture, of which 3.9 Mha will need to be restored (22% less than that of MIX-PAST) (table 2). The increased steers finishing in feedlots (33% of slaughtered animals) and the greater beef productivity per animal (57 kg CWE $head^{-1}$) in intensified systems will be responsible for this larger production from a smaller herd. In the MIX-FEED+ scenario, the larger share of steers finished in feedlots alongside the adoption of creep feeding will enable to meet the future planned demand for beef production in Mato Grosso by 2030 with a herd of only 35 Mhd (2.4 and 4.4 Mhd less than MIX-FEED and MIX-PAST scenarios, respectively). In the total of 24.7 Mha of pasture, 3.51 Mha will need to be restored (10% and 30% less than that of MIX-FEED and MIX-PAST, respectively) (table 2). In this scenario, the increase of weaning weight by the creep feeding and the 34% of slaughtered animals finished in feedlots (figure S6) result in greater beef productivity per animal (63 kg CWE $head^{-1}$) as the slaughter age is less than 29 months, which is responsible for the increased production volume from a smaller herd.

3.2. Investments and economic returns

Pasture restoration is an expensive form of intensification. This implies that the highest investment costs will occur in the MIX-PAST scenario that reforms the largest pasture area, followed by MIX-FEED, MIX-FEED+ and BASE (table 2). However, the lower productivity in BASE, in which the least intensification effort, will result in higher marginal investment. In MIX-FEED and MIX-FEED+ scenarios, the overall

Table 2. Current values and management scenarios outputs.

		2030			
Model results *Herd*	Current	BASE	MIX-PAST	MIX-FEED	MIX-FEED+
Number of animals (Mhd)[a]	29.1	38.3	39.4	37.5	35.1
Slaughtered animals (Mhd)[a]	5.29	7.45	8.82	8.42	8.39
Steers finished in feedlot (Mhd)[a]	0.89	1.67	1.73	2.85	2.82
Steers finished in semi-confinement (Mhd)[a]	0.32	0.54	0.59	0.45	0.41
Average age at slaughtering (Months)[b]	38.9	35.1	33.3	32.8	28.5
Overall stocking density rate (AU ha^{-1}) [a]	0.79	0.90	1.04	0.97	0.95
Stocking density rate of improved systems (AU ha^{-1})[b]	—	0.92	1.15	1.04	1.01
Productivity (kg CWE ha^{-1})[b]	45.5	66.8	95.8	93.6	94.6
Productivity (kg CWE head^{-1})[b]	40.0	48.0	55.0	57.3	62.9
Beef production (Mt CWE)[a]	1.18	1.79	2.08	2.04	2.06
Land use (Mha)					
Total pasture area[c]	24.8	28.0	25.1	25.0	24.7
Restored pasture area	—	2.80	5.00	3.90	3.51
Economic outputs					
Accumulated investment (US$ billion)	—	3.12	5.31	4.44	3.91
Operational costs (US$ ha^{-1})[b]	63.9	121	177	167	162
Operational costs (US$ head^{-1})[b]	56.1	86.8	102	102	108
Operational costs (US$ kg CWE^{-1})[b]	1.40	1.81	1.85	1.78	1.72
Profit margin (US$ ha^{-1})[b]	77.8	86.9	119	124	131
Profit margin (US$ head^{-1})[b]	60.3	62.5	68.5	75.7	86.9
Profit margin (US$ kg CWE^{-1})[b]	1.42	1.30	1.25	1.32	1.38
Net present value (US$ ha^{-1})[b,d]	—	619	684	765	840
GHG emissions (MtCO_2e)[e]					
Enteric CH_4[a]	61.0	74.7	73.7	70.2	68.5
Manure—CH_4[a]	1.42	1.73	1.70	1.63	1.59
Manure—N_2O[a]	6.15	8.73	9.41	8.93	8.32
Fertilizers—N_2O and CO_2[a]	0.4	3.29	5.77	4.58	4.21
Land use change[f]	—	– 0.03 (±0.03)	−0.04 (±0.04)	−0.10 (±0.07)	−0.13 (±0.09)
Manufacture inputs and machinery—CO_2[a]	0.61	2.09	3.11	2.74	2.98
Fossil fuels—CO_2[a]	0.11	0.20	0.24	0.29	0.35
Electrical energy—CO_2[a]	0.04	0.04	0.04	0.04	0.04
Sequestration CO_2[a]	—	5.36 (±1.32)	10.1 (±2.54)	7.98 (±1.99)	7.09 (±1.92)
Net emissions[a]	69.8	85.3 (±1.37)	83.8 (±2.61)	80.4 (±2.09)	78.8 (±2.05)
Relative GHG emissions (kg CO_2e head^{-1})[e]					
CH_4 enteric[b]	2098	1 951	1 863	1 871	1 949
Manure emissions—CH_4 and N_2O[b]	260	273	281	281	282
Net emissions[b]	2402	2 230 (±34.5)	2 117 (±64.1)	2 141 (±53.1)	2 241 (±54.6)
Net emissions (Kg CO_2e kg CWE^{-1})[b]	59.1	45.6 (±0.7)	37.4 (±1.2)	36.3 (±1.0)	35.0 (±0.9)

[a] For projected scenarios, it include both intensified and non-intensified systems.

[b] For projected scenarios, these values are from intensified areas. Values for non-intensified area are the same as of current.

[c] The three MIX-intervention scenarios occur in the context of strong environmental governance (Rochedo *et al* 2018), and therefore reflect similar rates of land use change, whereas the BASE scenario assumes higher deforestation rates. As such, pasturelands in the MIX-scenarios differ only as a function of the additional soy-corn cropland area needed to feed the herd.

[d] Unlike the other outputs, the values corresponds to 2012 since the future values are brought to the present.

[e] Values in parenthesis represent the uncertainty bounds.

[f] We account emissions from land use change to meet the additional cropland demand for feedstuff (table S4). We use regional management factors for the change in soil organic carbon (SOC) storage due to land use change (table S8). The negative signal means a carbon sequestration.

Note. US$ = R$ 2.35 (average value for 2014).

investments are, respectively, 17% and 28% lower than those of MIX-PAST for the same productivity per hectare. At the same time, system intensification implies an increase in operational costs due to supplementary feeding and pasture maintenance costs. The larger the share of grains in animal feeding, the higher is the operational cost per animal. Nevertheless, increased productivity pays off higher operational costs (table 2 and figure 3). It implies that in the MIX-PAST scenario, operational costs per animal in intensified systems are 6% lower than that of MIX-FEED+, but the larger herd size results in 9% higher costs per hectare. Additionally, the costs per unit of beef produced in the MIX-PAST scenario are

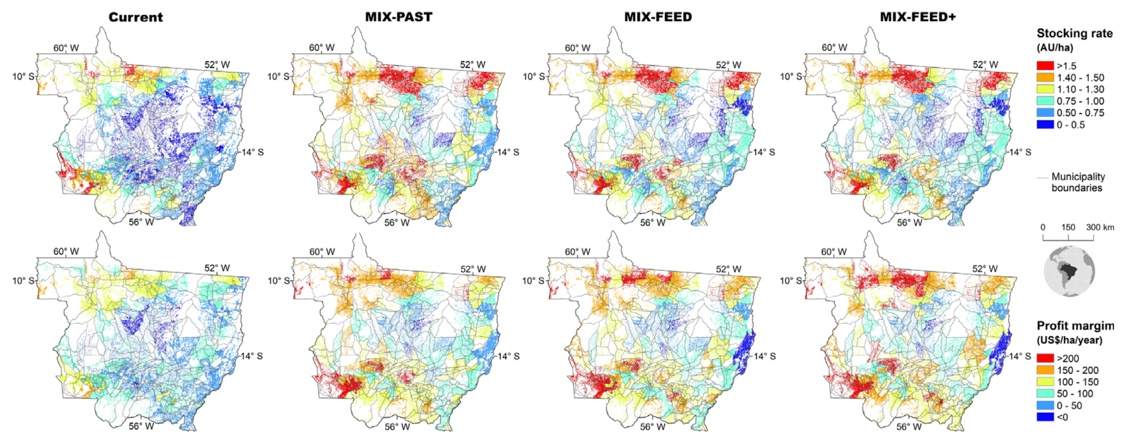

Figure 3. Current and modeled stock densities (AU/ha) and profit margin (US$/ha/year) by 2030 across mato grosso.

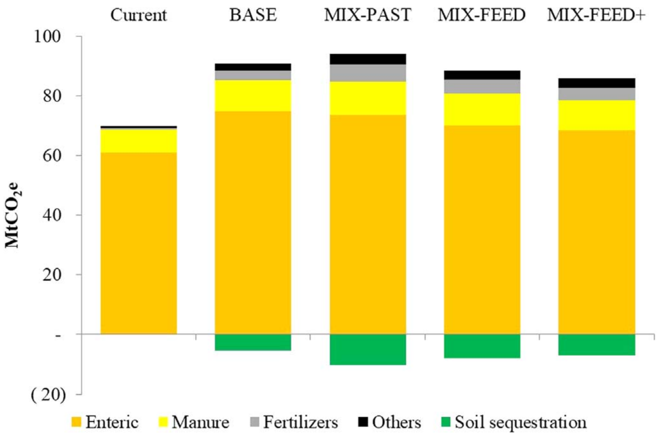

Figure 4. GHG balance per source, at the present (current) and under projected scenarios by 2030.

3.9% and 7.8% higher than that of MIX-FEED and MIX-FEED+, respectively.

In all scenarios, the return-on-investment is positive for most municipalities. In sum, the most economically viable scenario is MIX-FEED+, followed by MIX-FEED and MIX-PAST. Conversely, the least economically attractive scenario is the BASE, in which the average NPV is 26% lower than that of MIX-FEED+ (table 2).

3.3. GHG emissions and budgets

Livestock's major source of GHG is methane from enteric emissions. In Mato Grosso, these emissions amounted to 61 $MtCO_2e$ in 2012, which represents 87% of all GHG emissions. While this number is poised to increase as the herd grows (table 2), the share of methane to total GHG emissions varied between 76% and 82% in the projected scenarios (figure 4). In the intensification scenarios the largest emissions from enteric fermentation will occur in the MIX-PAST scenario (74 $MtCO_2e$) due to its bigger herd. Conversely, the MIX-FEED and MIX-FEED+ will emit 1.8 and 5.2 $MtCO_2e$ less, respectively (table 2), while producing the same amount of beef as in the MIX-PAST scenario. Emissions from manure (CH_4 and N_2O) are also proportional to the herd, even though concentrated feeding with higher protein content in both feedlots and improved pasture increases the ratio between manure/enteric emissions from the current 12%–15% by 2030. N_2O proportions in manure emissions rises from 81% to 85% in all scenarios by 2030 (figure 4 and table 2).

GHG emissions from fertilizers (CO_2 and N_2O) are proportional to the area of improved pasture (restoration and maintenance) and the area of cropland needed to produce the grains used in the animal's diet. In the MIX-PAST scenario, these emissions amount to 5.8 $MtCO_2e\ yr^{-1}$ by 2030 (6.1% of total emissions), that stem from pasture improvement (98%) and crops needed for feeding animals (2%). In the MIX-FEED and MIX-FEED+ scenarios, emissions from fertilizers amount to 4.6 and 4.2 $MtCO_2e\ yr^{-1}$, respectively, 21%–27% less than those of the MIX-PAST scenario. In the BASE scenario, these emissions will represent 3.6% of their total emissions by 2030 (table 2). We also account for the impacts of land use change for accommodate the additional demand for cropland to produce grains to feed the herd. As the

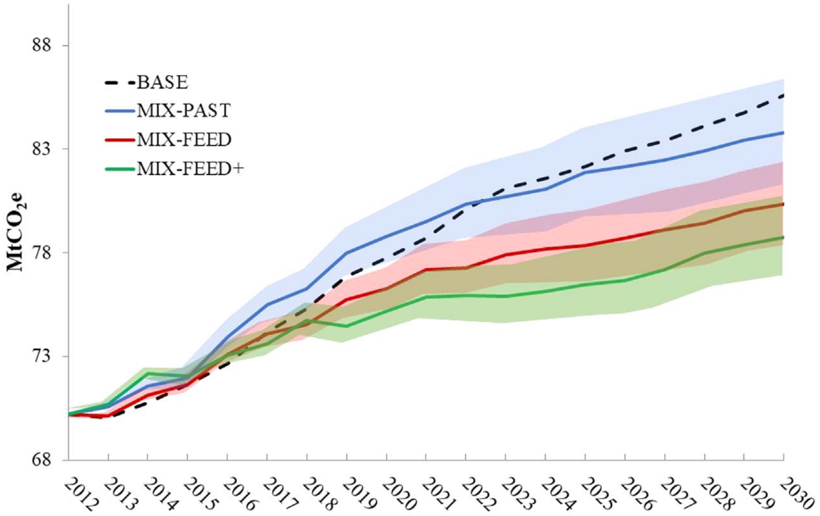

Figure 5. Net GHG emissions under modeled scenarios. Shadow areas depict uncertainty bounds.

transition from degraded pasture to no-till crops prevails in Mato Grosso, and since we use regional management factors for the change in SOC (table S8), all scenarios reflect a modest degree of carbon sequestration (table 2). Emissions associated with fossil fuels, electrical energy and the manufacture of inputs and machinery (CO_2) range from 2.3 $MtCO_2e\ yr^{-1}$ (BASE) to 3.9 $MtCO_2e\ yr^{-1}$ by 2030 (MIX-FEED+), reflecting only 2.6%–3.9% of total emissions.

Although all scenarios will increase overall GHG emissions (figure 5) due to an increasing beef production, our results also show some degree of sequestration due to intensification strategies. In the MIX-PAST scenario, the restoration of 5.0 Mha of pasture will sequester a total of 10 $MtCO_2e\ yr^{-1}$ in the soil by 2030, which is 27% and 43% more than in the MIX-FEED and MIX-FEED+ scenario, respectively. Despite this substantial sequestration, the MIX-PAST scenario is less advantageous compared to the MIX-FEED and MIX-FEED+ scenarios. The mitigation of marginal emissions is lower in the MIX-PAST scenario (42%) than in the MIX-FEED (43%) and MIX-FEED+ (44%) scenarios, but is still an improvement compared to the BASE scenario (26%). As such, the MIX-FEED+ scenario produces the same amount of beef as the MIX-FEED and MIX-PAST, but this production will entail 3.6% and 6.4% lower net emissions, respectively. This advantage is explained by the smaller number of animals and a lower emission coefficient per unit of beef produced in intensified systems, namely 35.0 kg CO_2e per kg of CWE versus 36.3 kg CO_2e per kg of CWE (MIX-FEED) and 37.4 kg CO_2e per kg of CWE (MIX-PAST) (table 2). By contrast, the BASE scenario stands out as the worst-case scenario, since it fails to meet the share of Mato Grosso to meet Brazil's future planned target of beef production and its emission coefficient is 45.6 kg CO_2e per kg of CWE, a reduction of only 23% in relation to that of no intensified cattle ranching systems (Current) (table 2).

4. Discussion

Our results show that, in comparison with current figures, all scenarios involve a substantial increase in GHG emissions, which corresponds with studies that assessed carbon footprint of beef production under different management strategies (Cardoso *et al* 2016, Cerri *et al* 2016). Among the different emissions sources, CH_4 emissions from enteric fermentation continue to be the main emission source. Moreover, all scenarios indicate a substantial investment needed for increasing beef production above current levels. In the BASE scenario, where the SIMPEC model simulates the continuation of historical trends, this production level (1.79 Mt CWE) is not sufficient to meet the projected demand (2.0 (Mt CWE). The intensification scenarios assume the attainment of this production target, but reveal substantial differences in terms of economic returns and carbon emissions. Based on these results, we argue that a mere focus on pasture restoration (MIX-PAST), as suggested in Brazil's NDC and ABC plan, is not the most optimal strategy mix for the intensification of the livestock sector.

Net emissions tend to decrease as intensification strategy mixes become more diversely proportioned. While a strong focus on pasture restoration (MIX-PAST) results in net emissions of 83.8 ± 2.61, these emissions tend to decrease in the MIX-FEED (80.4 ± 2.09) and MIX-FEED+ (78.8 ± 2.05) scenarios as feedlot finishing and creep feeding become more relevant. The same trend is found for the intensity of CH_4 emissions, which decreases from 35.4 kg CO_2e kg CWE^{-1} (MIX-PAST), 34.4 kg CO_2e kg CWE^{-1} (MIX-FEED) and 33.2 kg CO_2e kg CWE^{-1} (MIX-FEED+). One explanation for this is the shorter animal life span due to accelerated finishing, which reduces the emission time individual animals (figure S7) (Cota *et al* 2014). In addition, animal productivity is 8% and 11% higher in the MIX-FEED+ scenario compared to the

MIX-FEED and MIX-PAST scenarios, respectively, allowing for a smaller herd. The MIX-PAST scenario also has higher values for nearly all categories in comparison to the MIX-FEED+ scenario. A notable exception are CO_2 emissions from fossil fuels.

Soil carbon sequestration after pasture restoration does not compensate marginal herd emissions, because higher stock densities and higher beef production will lead to an overall rise in GHG emissions from the livestock sector. Moreover, the carbon sequestered in soils of restored pasture will be effective only as long as pastures remain productive, which depends on an increasing use of nitrogen-based fertilizers that are a source GHG emissions. This increase brings into question the impact of high demand for N, P and other nutrients on the limited world reserves (Cordell and Neset 2014, Sattari *et al* 2016). Technology or practices that significantly reduce the use of synthetic fertilizers (i.e. biological fixation of N by grasses or availability of P by microorganisms) may mitigate this offset to some extent, but it is unclear whether this may become available in the near future.

Although our analysis considered a fixed rate of carbon accumulation over the simulated time-period, 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). While we have considered only the top soil layer (0–30 cm) as recommended by IPCC, carbon sequestration could be much larger when considering deep soil layers. Notwithstanding these uncertainties, carbon accumulation in soils asymptotically tends to transition into a steady state equilibrium some time (≈20 years) after pasture restoration (IPCC 2006, Smith 2014), beyond which net emissions will rise more steeply due to the continued growth of the herd.

Supplementary grain-feed is an especially important strategy in view of the seasonality of forage production in Brazil. It is a key to maintaining an animal's weight gain throughout the year, especially in the dry season, when the animals face natural feed constraints due to low grass production. Environmental or social externalities apart (Werth *et al* 2014), feedlots also allow additional emission reductions by adequate reutilization of manure (Hristov *et al* 2013, Herrero *et al* 2016) to generate bioenergy (Palermo and Freitas 2014) or as substitute for synthetic fertilizers (Hristov *et al* 2013).

The economic gains from cattle intensification show similar trends as GHG emissions. Our results suggest that a more diverse proportion of the intensification practices in a strategy mix tend to have a better profit margin, reduces marginal operational costs and requires a lower cumulative investment (table 2). These positive effects may benefit from the favorable circumstances in Mato Grosso. Economic gains from cattle intensification naturally depend on beef prices along with local costs of inputs (grains, fertilizers). As the largest national producer, grain prices are the lowest in Mato Grosso (CEPEA 2016) and its ecological and economic conditions point towards a state that is poised for successful intensification (Barbosa *et al* 2015).

At the same time, some caution may be useful. Regarding beef prices, our sensitivity analysis (supplementary methods) indicates that net revenues may fluctuate as much as 26% as a function of 9% variation in beef prices. Aside from the recent spike in beef prices (figure S8), historical price trend shows a decline since the 1970s (De Zen and Barros 2005), which is the opposite to the trend of rising production costs. These opposite trends pose a challenge to the livestock sector as it is becoming increasingly competitive. Intensification by escalating production, instead of ensuing higher rents to ranchers, may exacerbate such a competition, perversely shrinking profit margins at the farm gate (Leonard 2014). Large-scale pasture restoration may therefore incur greater economic risk due to high investment costs and volatile input and output prices (table S9). These complications may constrain intensification strategies that are primarily focused on pasture restoration. Moreover, this may be exacerbated by other factors, including the lack of good bookkeeping capacity and the traditional risk-averse mindset of ranchers (Barbosa *et al* 2015), Brazil's cattle market oligopsony (Merry and Soares-Filho 2017) and its frequent economic instabilities (Grossi *et al* 2018).

Finally, it is important to consider that, as part of the ABC and NDC policies, Brazil has proposed a massive pasture restoration program with the dual aims of reducing GHG emissions and making ranching more competitive. As argued in the introduction, the combined target of these aims at 30 Mha of pasture restoration by 2030 for the entire country. If we pro-rate this target for the Mato Grosso state taking into account its regional potential for intensification (Barbosa *et al* 2015), we estimate that a 7 Mha of pasturelands in Mato Grosso would need be restored to meet such a national target (supplementary methods). It is clear that none of the scenarios in our analysis attain this level of restoration. Even the MIX-PAST scenario, for example, the restoration of 5.0 Mha would still require an additional 2.0 Mha in order to meet the NDC and ABC policy targets, which may allow for a further increase in beef production.

5. Conclusions

Increasing beef production will lead to an overall rise in GHG emissions from the cattle sector within a near future (figure 5). Even if improved tropical pasturelands can act as a carbon sinks, our results suggest that these sinks would mitigate only a part of marginal emissions and the larger the herd increases, the lower is the mitigated portion of marginal emissions. Indeed, a strategy for intensification heavily based on pasture restoration does reduce GHG emission compared to the baseline scenario, while increasing animal production. At the same time, our analysis demonstrates that an intensification strategy mix with a more diverse portfolio of practices, most notably grain-feed supplementation both for grazing and confined animals, will be more effective both in terms of economic returns and GHG emission reductions. As such, investments in enhanced nutritional management of the herd, specially by grain-feed supplementation either on pasture or in feedlots are more likely to prompt better economic, productive, and, in particular, environmental outlooks for the cattle sector in Brazil.

Although our analysis is limited to Mato Grosso, the implications of livestock intensification in this state may have consequences for adjacent areas. A more intensified livestock sector may put less pressure on the formation of new pastures, as illegal deforestation puts intensification investments at risk, if environmental embargos and bans of bank loans are truly enforced in the beef supply chain (Soares-Filho and Rajão *et al* 2018). At the same time, there is a need for further research on the consequences of this intensification on other agricultural sectors. For instance, a more commonplace use of grain-feed supplementation increases demand for other agricultural sectors and may in turn drive indirect demand for new land (Barona *et al* 2010, Arima *et al* 2011), although this can be partially compensated with the expansion of double cropping systems. Such analysis may shed more light on the possibilities for mixing different intensification strategies in order to optimally meet economic and environmental targets.

Finally, our study has exclusively focused on one ecosystem service (gas regulation—Costanza *et al* 2017). Future research efforts may need to investigate other environmental benefits of livestock intensification in order to complement our analysis of GHG emissions.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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