Sustainable intensification of Brazilian livestock production through optimized pasture restoration

de Oliveira Silva, R; Barioni, LG; Hall, JAJ; Moretti, AC; Veloso, RF; Alexander, P; Crespolini, M; Moran, D

Published in:
Agricultural Systems

DOI:
10.1016/j.agsy.2017.02.001

First published: 20/02/2017

Document Version
Peer reviewed version

Link to publication

Citation for pulished version (APA):
de Oliveira Silva, R., Barioni, LG., Hall, JAJ., Moretti, AC., Veloso, RF., Alexander, P., Crespolini, M., & Moran, D. (2017). Sustainable intensification of Brazilian livestock production through optimized pasture restoration. *Agricultural Systems*, *153*, 201 - 211. Advance online publication. https://doi.org/10.1016/j.agsy.2017.02.001

DOI: 10.1016/j.agsy.2017.02.001

Sustainable intensification of Brazilian livestock production through optimized pasture restoration

Rafael de Oliveira Silva[a,b,*], Luis Gustavo Barioni[c], Julian A. J. Hall[b], Antonio Carlos Moretti[d], Rui Fonseca Veloso[e], Peter Alexander[a], Mariane Crespolini[f], Dominic Moran[a,g]

[a]Research Division, SRUC, West Mains Road, Edinburgh, EH9 3JG, Scotland.
[b]School of Mathematics, University of Edinburgh, Mayfield Road, Edinburgh, EH9 3JZ, Scotland.
[c]Embrapa Agriculture Informatics, CEP 13083-886 Campinas-SP, Brazil.
[d]Department of Applied Mathematics, University of Campinas, 13083-970, Campinas SP, Brazil.
[e]Embrapa Cerrados, CEP 73301-970 Planaltina-DF, Brazil.
[f]Institute of Economics, University of Campinas, 13083-857, Campinas SP, Brazil.
[g]Environment Department, University of York, University Rd, York, YO10 5DD, UK

*Corresponding author: Rafael.silva@sruc.ac.uk

E-mail address: Rafael.silva@sruc.ac.uk (Silva), luis.barioni@embrapa.br (Barioni), J.A.J.Hall@ed.ac.uk (Hall), moretti@ime.unicamp.br (Moretti), rui.veloso@embrapa.br (Veloso), peter.alexander@ed.ac.uk (Alexander), macrespolini@gmail.com (Crespolini), dominic.moran@sruc.ac.uk (Moran).

Abstract

Grassland degradation compromises the profitability of Brazilian livestock production, and pasture recovery is a promising strategy for sustainable intensification of agriculture (SAI). Recovery increases carbon sequestration into the soil and can potentially avoid deforestation; thereby reducing emissions intensity (EI), but only at increased investment cost per unit of area. We develop a multi-period linear programming (LP) model for grazing beef production planning to represent a typical *Cerrado* stocking and finishing beef farm. We compare economic and environmental performance of two alternative optimized pasture management approaches relative to the traditional practice (TRP), which is based on restoring pasture after a full degradation cycle of 8 years. The scenarios considered the difference made by access to subsidized credit through the Low Carbon Agriculture program ("Programa ABC"). The model estimates EI using upstream life cycle assessment (LCA), and dynamically estimates soil organic carbon (SOC) changes as a function of pasture management. The results show net present values (NPV) ranging from -67 Brazilian reals per hectare-year (R$.ha^{-1}yr^{-1}) to around 300 R$.ha^{-1}yr^{-1}, respectively for traditional and optimized pasture management strategies. Estimated EI of the TRP is 11.50 kg CO_2 equivalent per kg of carcass weight equivalent (kg CO_2e/kg CWE) relative to 3.59 kg CO_2e/kg CWE for optimized management. Highest emission abatement results from improved SOC sequestration, while access to credit could further reduce EI by around 20%. We consider the effects of alternative credit interest on both NPV and EI. The results provide evidence to inform the design of Brazil's key domestic policy incentive for low carbon agriculture, which is an important component of the country's Intended Nationally Determined Contributions (INDC) on emissions mitigation. The results also contribute to the global debate on the interpretation of SAI.

Keywords: Sustainable agricultural intensification, grassland management, linear programming, soil organic carbon

Highlights

- Greenhouse gas emissions form Brazilian livestock are globally significant but more than half of production is on degraded pastures.
- An optimization model indicates that alternative partitioned pasture restoration practices could out-perform traditional practices in terms of profitability and reduced emissions.
- Improved management means soil organic carbon sequestration could abate up to 85% of cattle emissions per kilogram of meat produced (CH_4 and N_2O) from stocking to finishing.

1. Introduction

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

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

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

The need for investment to address the nexus of pasture degradation, low productivity and food security and emissions is recognised as a national policy priority in Brazil, with restoration encouraged through the creation of a government-funded bank credit line for low carbon agriculture, the *Agricultura de Baixo Carbono* (ABC) - Low Carbon Agriculture program (Mozzer, 2011). To date, this program has not been subject to any formal economic analysis considering the economic return to the adoption of restoration practices. The restoration issue is also of sufficient global prominence to have been central to Brazil's mitigation commitments under the United Nations Framework Convention on Climate Change.   At the 15th Conference of the Parties (COP15) in 2009, the country proposed a voluntary emissions reduction target of around 40% relative to baseline emissions by 2020 to be achieved by its Nationally Appropriate Mitigation Actions (NAMAs) (Mozzer, 2011). At COP21 (2015), the commitment was nominally converted into an Independently Determined National Contribution (INDC) (Brazil, 2015), which proposed a further mitigation target of 43% reduction by 2030 relative to 2005 emissions. Both NAMAs and INDCs focus on reduced deforestation in the Amazon and the *Cerrado*, and include respectively the restoration of 15 million hectares (M ha) of degraded pastures between 2010-2020, and a further 15 M ha from 2020-2030.

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

2. Methods

2.1 Overview

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

2.2 Mathematical modelling of restoration practices

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

Based on the pasture degradation definition of Macedo and Zimmer (1993), the model imposes a deterministic decline in dry matter productivity (DMP) with time. DMP levels (in tonnes of dry matter per hectare year) are represented by *{P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,P11}*. As the symbols are ordered in decreasing levels of DMP, the degradation process is represented as the annual transference between consecutive levels, i.e., *P1* degrades to *P2* after one year of formation of pasture *P1,* if no interventions are undertaken; *P2* degrades to *P3* in the following year, and so forth, until *P10*, which degrades to *P11*, the minimum degradation level (ecosystem equilibrium), thus *P11* “degrades” to *P11*. Because there are 11 DMP levels and each level is one-year “distance” from its consecutive, the whole degradation process takes 10 years. The traditional restoration practice (TRP) is equivalent to restoration only when *P10* or *P11* are reached.

In contrast this paper models other two optimized approaches: The Fractional Restoration Practice (FRP) and the Uniform Restoration Practice (URP). URP permits restoration of the whole pasture at any point during the degradation process, e.g., DMP level *P5* could be restored to *P4*, *P3*, *P2* or *P1* or maintained at *P5* instead of degrading to *P6* at any time. FRP extends URP and allows for fractions of pasture area to be restored to different DMP levels, e.g., any fraction of pasture *P5* could be restored to *P1*, other fractions to *P2* and *P5,* and even a fraction may degrade to *P6*. In this way, a given pasture area is then partitioned into sub-areas instead of a uniform area as is the case in TRP and URP. The annual average values of the DMP levels are presented in Table 5 (Data section)

2.3 Mathematical description

2.3.1 Model's overview

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

The model focuses on optimizing decisions for pasture management while maximizing profit subject to biological and financial constraints. Stocking rates and, therefore, total output depend on feed production from pasture and consumption patterns driven by herd dynamics. The model accounts for intra- and inter-annual variations of pasture productivity and represents the processes of pasture degradation and restoration to optimize decisions on restoration from an economic perspective.

The model was implemented in AIMMS algebraic language (Bisschop, 2011), comprising approximately 7000 variables and 4300 constraints for a 20 year planning period, and was solved using the CPLEX solver (CPLEX, 2009).

Tables 1-3 provide the general notation used to describe the model.

Table 1: Symbols for indices and functions of sets used in the mathematical description of the model

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

Table 2: Symbols for Decision Variables

Symbol	Description	Unit
G_m	Cash income in month m	R$
H_m	Cash outcome in month m	R$
F_m	Cash in month m	R$
V_t	Loan taken in year t	R$
PV_t	Installment of loan paid in year t	R$
$X_{m,k}$	Purchased steers of age cohort k in month m	Head
$Y_{m,k}$	Stocked steers of age cohort k in month m	Head
W_m	Transferred dry matter from month m to $m + 1$	Kg
$Z_{t,p}$	Area of pasture p in year t	Ha

Table 3: Symbols and values for model parameters

Symbol	Description	Value	Unit
$dm_{p,o}$	Initial herbage mass (dry-matter) of pasture level *p*	4000	kg.ha^{-1}
$A_{p,o}$	Initial area of pasture level *p*	See section 2.5	ha
A	Total pasture area	600	ha
l_{cr}	Credit limit	1000000	R$
γ_{cr}	Amortization system parameter[1]	0.234	dimensionless
FC	Farm fixed costs	3.66	R$.ha^{-1}.mth^{-1}
α_k	Dry matter intake of animal of steer age cohort *k*	Table 4	kg.hd^{-1}.mth^{-1}
$\eta_{q,p}$	Cost of restoration from pasture level *q* to level *p*	Table 4	R$.ha^{-1}
λ_k	Cattle maintenance cost for age cohort *k*	Table 4	R$.hd^{-1}
μ_k	Mortality rate of steer age cohort *k*	Table 4	dimensionless
π	Transaction cost of purchasing cattle	30	R$.hd^{-1}
$\rho_{p,M}$	Productivity of pasture level p in calendar month *M*	Table 5	kg.ha^{-1}.mth^{-1}
σ_M	Fraction of herbage mass loss due to senescence	0.00014	dimensionless
θ_k	Selling price of steer age cohort *k*	Table 4	R$.hd^{-1}
τ_M	Minimum herbage mass transference at month *M*	1000(drought) 2000(rainy)	kg.ha^{-1}.mth^{-1}
ξ	Fraction of herbage mass loss due to grazing animals (grazing efficiency)	0.6	dimensionless

[1] Amortization parameter was calculated using the formula $\gamma = ir\left(1-\frac{1}{(1+ir)^{np}}\right)^{-1}$, where *ir* represents the ABC program interest rate (5.5% per annum) and *np* the number of payments. i.e., five parcels according to “ABC Recuperação” – ABC Pasture Recovery[1]. Multiplying γ_{cr} by the loan gives the value of instalments.

2.3.2 Pasture dynamics

---

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

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

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

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

Where p and q indexes correspond to the order of elements in Ω; q is auxiliary index in the same set as p. The first term in the right hand side (RHS) of Eq.1 represents degradation. The second term in the RHS represents the restoration dynamics; the first term in the sum $\Sigma\, RZ_{t,q,p}$ represents the area transferred from all other partitions to p and $\Sigma\, RZ_{t-1,p,q}$ sums up the area that is removed from p (restored) to any more productive level q.

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

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

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

$$\sum_{p} \rho_{p,M} Z_{T_y+1,p} \geq \sum_{p} \rho_{p,M} Z_{t=1,p} \quad M = \text{Jan} \quad (3)$$

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

$$Z_{t=1,p} = A_{p,o} \quad \forall p \quad (4)$$

2.2.3 Herd dynamics and stocking rates

The model represents animal growth by defining age cohorts *k* with fixed attributes (e.g. body weight and feed intake, Table 4). Fattening is modelled as the transfer from age cohorts as follows:

$$Y_{m,k} = X_{m,k} + (1-\mu_{k-1})Y_{m-1,k-1} + \sum_{j}\prod_{i=1}^{j}(1-\mu_{k-i})^{3}X_{m-3j,k-j} - \sum_{j}\prod_{i=1}^{j}(1-\mu_{k+1-i})^{3}X_{m-3j,k-j+1} \quad (5)$$
$$k < 10, \quad j \in \{1,2,..\} \quad \forall m$$

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

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

$$Y_{m.,k} = \sum_{j} \prod_{i=1}^{j} (1-\mu_{k-i})^3 X_{m-3j,k-j} \quad k=10\,,\, j \in \{1,2,..\} \qquad (6)$$

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

$$(1+\xi)\sum_{k} \alpha_k Y_{m,k} + W_m \leq dm_{p,o} A_{p,o} + \sum_{k} \rho_{p,M} Z_{t(m),p} \quad m=1 \qquad (7)$$

And:

$$(1+\xi)\sum_{k} \alpha_k Y_{m,k} + W_m \leq \sum_{k} \rho_{p,M} Z_{t(m),p} + (1-\sigma_{M(m)}) W_{m-1} \quad 1 < m \leq T_m \quad (8)$$

Equation 9 is used to constraint the above-ground biomass inaccessible to the animals, i.e., there is a minimum value of forage per area that will have to be transferred to the following month:

$$W_m \geq \tau_{M(m)} A \quad \forall m \quad (9)$$

2.3.4 Revenue flow

Income (G_m) is generated from steers sold for slaughter.

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

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

$$H_m = FC * A + \sum_{k=1}^{8} (\pi + \theta_k) X_{m,k} + \sum_k \lambda_k Y_{m,k} + PI_m \sum_p \sum_q \eta_{p,q} RZ_{t(m),p,q} \quad \forall m \quad (11)$$

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

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

$$F_m = V_{t(m)} + G_m - H_m \quad m = 1 \quad (12)$$

And the credit lines must meet the credit limit:

$$V_{t(m)} \leq l_{cr} \quad \forall t \quad (13)$$

The credit line in Eq. 12 (variable V_t) is paid in 5 instalments (PV_t) after the third year of contract:

$$PV_t = \sum \gamma_{cr} V_{t-(3+i-1)} \quad \forall t \quad (14)$$

Along the planning period, cash flow is given by:

$$F_m = (1-i)F_{m-1} + TI_m \sum_{cr} V_{t(m),cr} - PI_m \sum_{cr} V_{t(m)} + G_m - H_m \quad 1 < m < T_m \quad (15)$$

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

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

$$F_m = (1-i)F_{m-1} - G_m + H_m - \sum_k \theta_k Y_{m,k} + \sum_p \sum_q \eta_{p,q} RZ_{t(m)+1,p,q} \quad m = T_m \quad (16)$$

The objective function is to maximize the final cash:

$$Max \quad F_{T_m} \quad (17)$$

2.3.5 GHG emissions and SOC stocks

The model estimates GHG using emissions factors for activities within the notional farm gate. Emissions associated with farm activities are: (a) CH_4 from cattle enteric fermentation (CH_4 from excreta is not accounted); (b) Direct and indirect N_2O

from manure; (c) Direct and indirect N_2O emissions from N fertilization; (d) CO_2 from changes in SOC stocks; and (e) LCA factors for inputs and farm operations applied in land use change and restoration practices. Items (a) and (b) depend on herd composition: each age cohort has an associated emission factor of CH_4 and N_2O (Equation 18).

$$ce_m = \sum_k (21 * \mathrm{CH4}_k + 310 * \mathrm{N2O}_k) Y_{m,k}, \ \forall m \quad (18)$$

Eq. 18 accounts for emissions converted to carbon dioxide equivalent for each cattle age cohort *k*, where ce_m is the total cattle emissions in month *m*; $CH4_k$ *and* $N2O_k$ are the emissions factors for CH_4 and N_2O (in $\mathrm{kg.hd^{-1}.mth^{-1}}$) for steers of age cohort *k* (Table 4), 21 and 310 are respectively the CH_4 and N_2O equivalence in CO_2e - in global warming potential for 100 years (GWP-100).

Due to the lack of studies in Brazilian conditions, for (c), we used the Intergovernmental Panel on Climate Change - IPCC Tier 1 default factor of 1% and 0.2% (Eggleston et al., 2006) , respectively for direct and indirect N emissions.

$$fe_t = 310 * cv_{N \rightarrow N_2O} \sum_p \sum_q NA_{p,q} RZ_{t(m),p,q} \quad (19)$$

Eq. 19 accounts for the emissions from N based fertilizers in year *t* (fe_t). The term inside the sum gives the amount of N applied for all pasture restoration options. The factor $cv_{N \rightarrow N2O}$ corresponds to the proportion of N converted into N_2O.

For (d), the emissions are calculated by modelling SOC dynamics. The model works with equilibrium values of the C stock for each pasture type (Table 5). The equilibrium values and equilibrium time horizon were calculated exogenously, using simulations from the CENTURY model (Parton et al., 1987) applied to *Cerrado* biophysical characteristics and using the annual dry mater productivity calculated for each pasture DMP level.

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

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

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

$$\frac{dc_{t,p}}{dt} = i_{t,p} - r_{t,p} \quad (20)$$

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

$$\frac{dc_{t,p}}{dt} = F - \rho_j c_{t,p} \quad (21)$$

At steady state $dc_t/dt = 0$:

$$\frac{dc_{t,p}}{dt} = 0 \Rightarrow c^*{}_{t,p} = \frac{F}{\rho} = \varepsilon_j \quad (22)$$

Where $C^*{}_{t,p} = \varepsilon_p$ is the SOC of pasture p at equilibrium. Thus (21) can be written as:

$$\frac{dc_{t,p}}{dt} = \rho_p(\varepsilon_p - c_{t,p}) \quad (23)$$

Writing as difference equations (discrete-time analogue):

$$\Delta c_{t,p} = \rho_p(\varepsilon_p - c_{t-1,p}) \quad (24)$$

Thus, SOC accumulation is given by:

$$c_{t,p} = c_{t-1,p} + \rho_p(\varepsilon_p - c_{t-1,p}) \quad (25)$$

Given the equilibrium values of each pasture DMP level (ε_p), carbon respiration losses (ρ_p) and initial SOC stock ($c_{0,p}$), equation (25) estimates SOC at any time t. The parameter ρ_p can be calibrated to adjust an assumed equilibrium time, or obtained exogenously, e.g., by calibrating against the CENTURY model (Parton et al., 1987).

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

$$c^H{}_t = \sum_p w_{t,p} c_{t,p} \quad (26)$$

Applying (25) in (26):

$$c^H{}_t = \sum_p w_{t,p} c_{t-1,p} + \rho\left(\sum_p w_{t,p}\varepsilon_p - \sum_p w_{t,p} c_{t-1,p}\right) \quad (27)$$

Substituting (26) into (27):

$$c^H{}_t = c^H{}_{t-1} + \rho\left(\sum_p w_{t,p}\varepsilon_p - c^H{}_{t-1}\right) = c^H{}_{t-1} + \rho\left(\varepsilon^H - C^H{}_{t-1}\right) \quad (28)$$

Since the total area is fixed ($\sum_p Z_{t,p} = A$), Eqs. 26-28 are linear relations.

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

$$\Delta c^{H}{}_{t} = \sum\nolimits_{p} \Delta c_{t,p} \quad \forall t \quad (29)$$

From (27):

$$\Delta c^{H}{}_{t} = \rho \left(\sum_{p} w_{t,p} \varepsilon_{p} - \sum_{p} w_{t,p} c_{t-1,p} \right) \quad (30)$$

Imposing that $w_{t,p}(\varepsilon_q - c_{t-1,q}) = 0$ if $p \neq q$, (30) can be rearranged as:

$$\Delta c^{H}{}_{t} = \rho \sum_{p} w_{t,p} \sum_{p} \left(\varepsilon_{p} - c_{t-1,p} \right) \quad (31)$$

Since $\sum_{p} w_{t,p} = 1$ (32)

$$\Delta c^{H}{}_{t} = \rho \sum_{p} \left(\varepsilon_{p} - c_{t-1,p} \right) = \sum_{p} \Delta c_{t,p} \qquad (33)$$

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

$$le_{t} = \sum_{inp} lca_{inp} \sum_{p} \sum_{q} INA_{inp,p,q} RZ_{t,p,q} \quad (34)$$

Eq. 34 gives the annual LCA emissions of (f) by accounting for the total application of a given input (or farm operation) *inp* in year *t* (term inside the double sum) and multiplying it by the input LCA emission factor, and then summing over *inp*. Where lca_{inp} represents the emission factor of input *inp*; $INA_{p,q}$ the amount of applied input *inp* associated with pasture restoration from pasture p to q (variable $RZ_{t,p,q}$).

2.4 Data

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

Direct cattle CH_4 emissions (Table 4) were calculated using Tier 2 methodology (Eggleston et al., 2006). Direct N_2O emissions from manure were estimated using a modified IPCC Tier 2 method. This follows recommendations in previous studies, e.g. Lessa et al. (2014) suggesting that urine and faeces have significantly different emissions factors under typical low protein content diets in Brazil, and that under such conditions, N excretion can be higher in faeces than urine (Xavier et al., 2014). Lessa et al., (2014) estimated N excretion separately for urine and faeces with respective emission factors derived from Brazilian studies (Cardoso et al., 2016).

Table 4: Steer bioeconomic and emissions data

Age cohort	Age (months)	Mortality[a] ($\%.mth^{-1}$)	Avg SBW[b] ($kg.hd^{-1}$)	DMI[c] ($kg.mth^{-1}$)	Price[d] ($R\$.hd^{-1}$)	Maintenance Cost[e] ($R\$.hd^{-1}.mth^{-1}$)	CH_4[f], $kg.head.^{-1}.mth^{-1}$	N_2O[g], $kg.head.^{-1}.mth^{-1}$
1	[6,9)	0.42	189	155.3	658	1.74	3.35	0.017
2	[9,12)	0.42	222	175.2	691	1.95	3.78	0.020
3	[12,15)	0.2	255	194.4	802	2.19	4.19	0.023
4	[15,18)	0.2	289	213.5	913	2.4	4.6	0.025
5	[18,21)	0.2	322	231.5	1,044	2.61	4.99	0.027
6	[21,24)	0.2	355	249.1	1,158	2.82	5.37	0.030
7	[24,27)	0.03	388	266.3	1,271	3.06	5.74	0.032
8	[27,30)	0.03	421	283.1	1,411	3.27	6.1	0.034
9	[30,33)	0.03	454	299.6	1,526	3.48	6.46	0.036
10	[33,36)	0.03	490	317.2	1,278	3.72	6.84	0.038

[a] Cited in Arruda and Corrêa (1992)

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

[c] Dry matter intake (DMI) as estimated by the National Research Council model (NRC 2000)

[d] Prices were based on time series collected from the Institute of Applied Economics (IEA, 2012) and were deflated to 2012 values using Fundação Getúlio Vargas (FGV 2012). Brazilian reals (R$) are expressed in 2012 values (1 R$-2012 is equivalent to 0.49 US$-2012)[2]

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

[f,g] Details of parameters used for emissions factor calculation are described in Table S1.

Pasture productivity (Table 5) for each level in Ω = *{P1,P2,P3,P4,P5,P6,P7,P8, P9,P10,P11}* was estimated using the Invernada software (Barioni, 2011), which uses monthly averages of historical climate data and the amount of N applied to estimate forage potential accumulation rates, according to the model of Tonato et al. (2010) for the main grass species used in Brazil.

---

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

Table 5: Pastures accumulation rates and equilibrium C stock values as a function of pasture type (*Brachiaria brizantha cv. Marandu*)

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

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

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

The restoration costs (in R$-2012 per hectare) in Table 6 (the values of $\eta_{p,q}$) were calculated as a function of the individual application of inputs and services employed in restoration practices. We assume the cost of restoring pasture from *p* to *q*, where *p* and *q* can be any element in Ω, is given by the cost of inputs/machinery used to maintain pasture *p* (because the restoration decision is made at the moment of degradation) added the cost required to restore one hectare from degraded level *P11* to *q*, less the cost of inputs to restore one hectare from level *P11* to *p*, but only positive differences in the amount of inputs/machinery are accounted for. Let $ap_{inp,P11,q}$ be the amount of inputs/machinery required to restore one hectare of pasture level *P11* to level *q*. Then $\eta_{p,q}$ is given by:

$$\eta_{p,q} = \sum_{inp} c_{inp}(ap_{in,p,p} + ap_{inp,P11,q} + ap_{inp,P11,p}) \quad (35)$$

The LCA emission coefficients for the inputs and machinery operations account for all upstream involved GHG emissions in their life cycle, from extraction of natural resources to production at the farm gate, except for purchased calves. Purchased calves are not specific but constant for the restoration practices, therefore not affecting the optimal solution. Base process data was collected from the inventory Ecoinvent v.2.2 (Ecoinvent, 2014) and processed in SimaPro v. 7.3.3 software (“SimaPro Analyst,” 2011). We followed the IPCC (2007), v. 1.02 methodology for calculating emissions in GWP over a 100 year timespan (Eggleston et al., 2006). The list of all inputs and farm operations included in the analysis and associated LCA emissions factors (lca_{inp}) can be found in De Oliveira Silva et al.(2016).

Table 6: Cost of pasture restoration management options[a]

	$\eta_{p,q}$ (R\$.ha^{-1})										
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
P1	267.0										
P2	364.8	222.0									
P3	462.6	319.8	177.0								
P4	525.2	382.4	239.6	106.5							
P5	587.8	445.0	302.2	169.0	35.9						
P6	767.1	624.3	481.5	348.4	215.2	29.2					
P7	946.4	803.6	660.8	527.7	394.6	208.5	22.4				
P8	1055.9	913.1	770.3	637.2	504.0	318.0	131.9	18.1			
P9	1165.4	1022.6	879.7	746.6	613.5	427.4	241.4	127.6	13.8		

P10	1204.2	1061.4	918.6	785.5	652.4	466.3	280.2	166.4	52.6	6.9	
P11	1243.1	1100.3	957.5	824.4	691.2	505.2	319.1	205.3	91.5	45.7	0.0

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

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

Table 7: Farm annual maintenance costs

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

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

To start production, the farmer is allowed to take a loan (variable $V_{t,cr}$) in the first year from the ABC program. The credit conditions for cattle breeders investing in pasture restoration are a limit of 1 million Brazilian reals (R$) and the payment can be made in 5 instalments with a three year grace period and an interest rate of 5.5% per annum (http://www.bndes.gov.br/apoio/abc.html).

2.5 Farm initial state scenarios

The quality of the pastures (or the level of degradation) before production starts, is an important factor when assessing the effectiveness of restoration practices. Three initial farm degradation scenarios are assumed: the Low Pasture Productivity (LPP), with initial pasture area corresponding to the whole area at DMP level *P7* (8.7 t $DM.ha^{-1}.yr^{-1}$); the Intermediate Pasture Productivity (IPP), with initial pasture area at DMP level *P5* (12.6 t $DM.ha^{-1}.yr^{-1}$); and the High Pasture Productivity (HPP), with initial pasture area at DMP level *P1* (19.6 t $DM.ha^{-1}.yr^{-1}$). We compared the traditional pasture management with the proposed optimized restoration practices with initial investments subjected to available capital with and without government subsidies for intensification through access to ABC credit.

2.5 Shadow price of carbon

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

$$\sum_t ce_t + \sum_t \Delta c^H{}_t + \sum_t fe_t + \sum_t le_t \leq E_{BAU} \quad (36)$$

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

3. Results

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

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

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

In contrast to TRP, optimizing pasture restoration though FRP or URP reduces the importance of the initial degradation level; NPV of 273.4 R\$.ha^{-1}.yr^{-1} and 274.5 R\$.ha^{-1}.yr^{-1}, respectively for LPP and HPP initial productivity scenarios (without ABC credit). As expected, the annual average stocking rates are also less dependent on initial productivity. The reason is that taking the alternative restoration practices leads to optimal stocking rates more efficiently, with minimum costs and less time required. The average stocking rates were around 1.6 animal units per hectare (AU.ha^{-1})[3], which accords with carrying capacity suggested by Strassburg et al. (2014).

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

Figure 1C shows that FRP could require less investment in restoration than TRP; e.g., investments are 62,700 R\$ and 69,800 R\$ per year, respectively for the FRP and the TRP under LPP (no ABC), while the average restoration area is around 3 times greater for the FRP than TRP (Figure 1D).

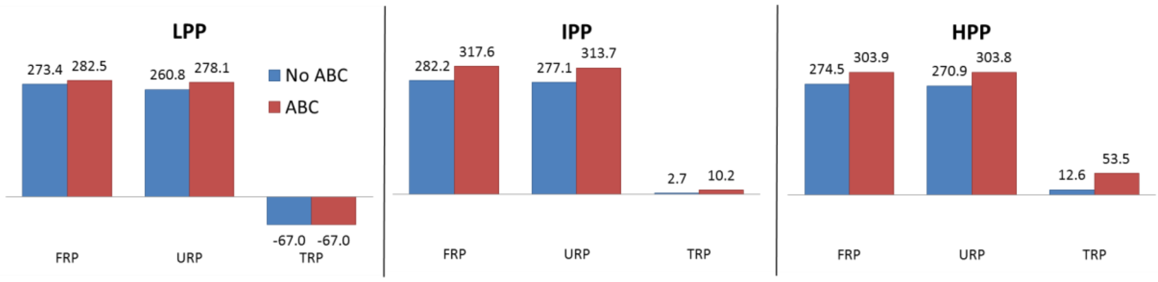
---

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

Although the credit promotes more investment per year in restoration, Figure 1D shows less area is restored per year when the credit is available. Because ABC increases cash incomes, more intensive restoration options are undertaken, reducing the average restoration area but improving forage productivity.

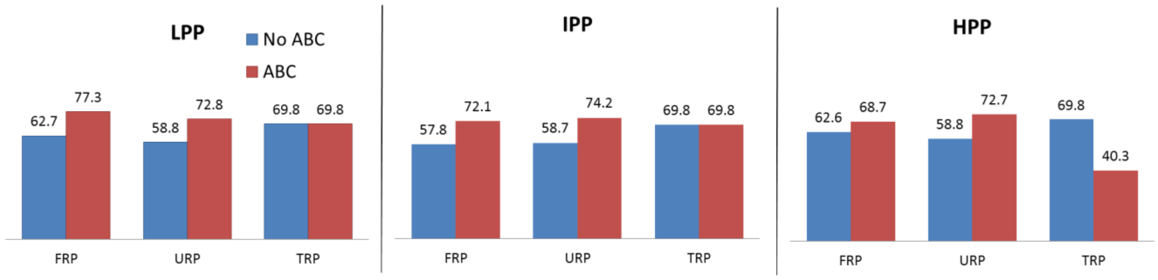
Figure 1E shows that the TRP beef productivity ranges from 96 to 104.7 kg CWE.ha^{-1}.yr^{-1} (without ABC) and 167.6 kg CWE. ha^{-1}.yr^{-1} (with ABC). Optimizing pasture restoration could double or triple beef productivity if combined with the ABC credit (Fig. 1E).

(a) Net present value (R$2012.ha^{-1}.yr^{-1})

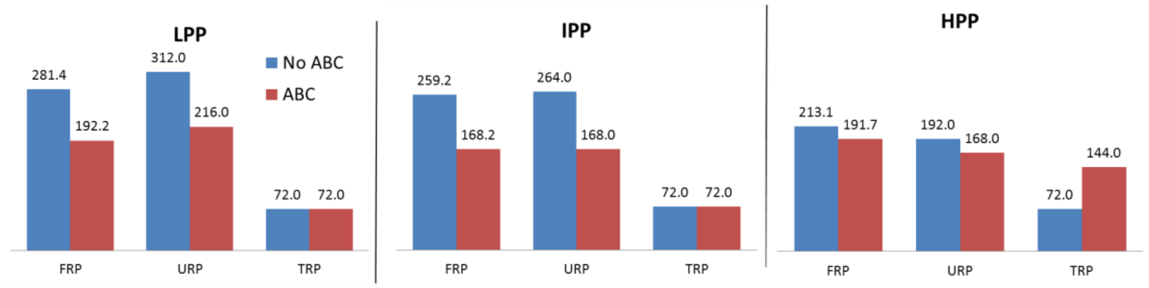


(b) Stocking rates (AU.ha^{-1})

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



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



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

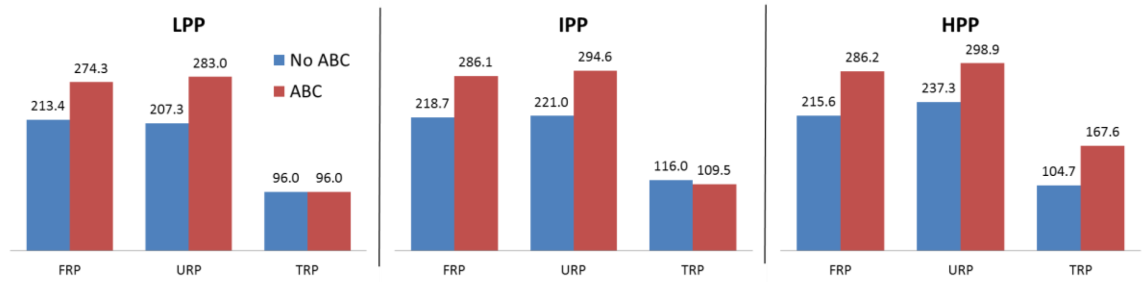


Figure 1: Comparison of economic returns depending on initial degradation scenarios (LPP, IPP, and HPP) and access to ABC credit.

Figures 2A-C provide graphical representation of the pasture management practices, i.e., pasture composition in terms of pasture types defined in Table 6, and the associated forage productivity in tonnes of dry matter per hectare per year (t DM.ha^{-1}.yr^{-1}), under the LPP scenario.

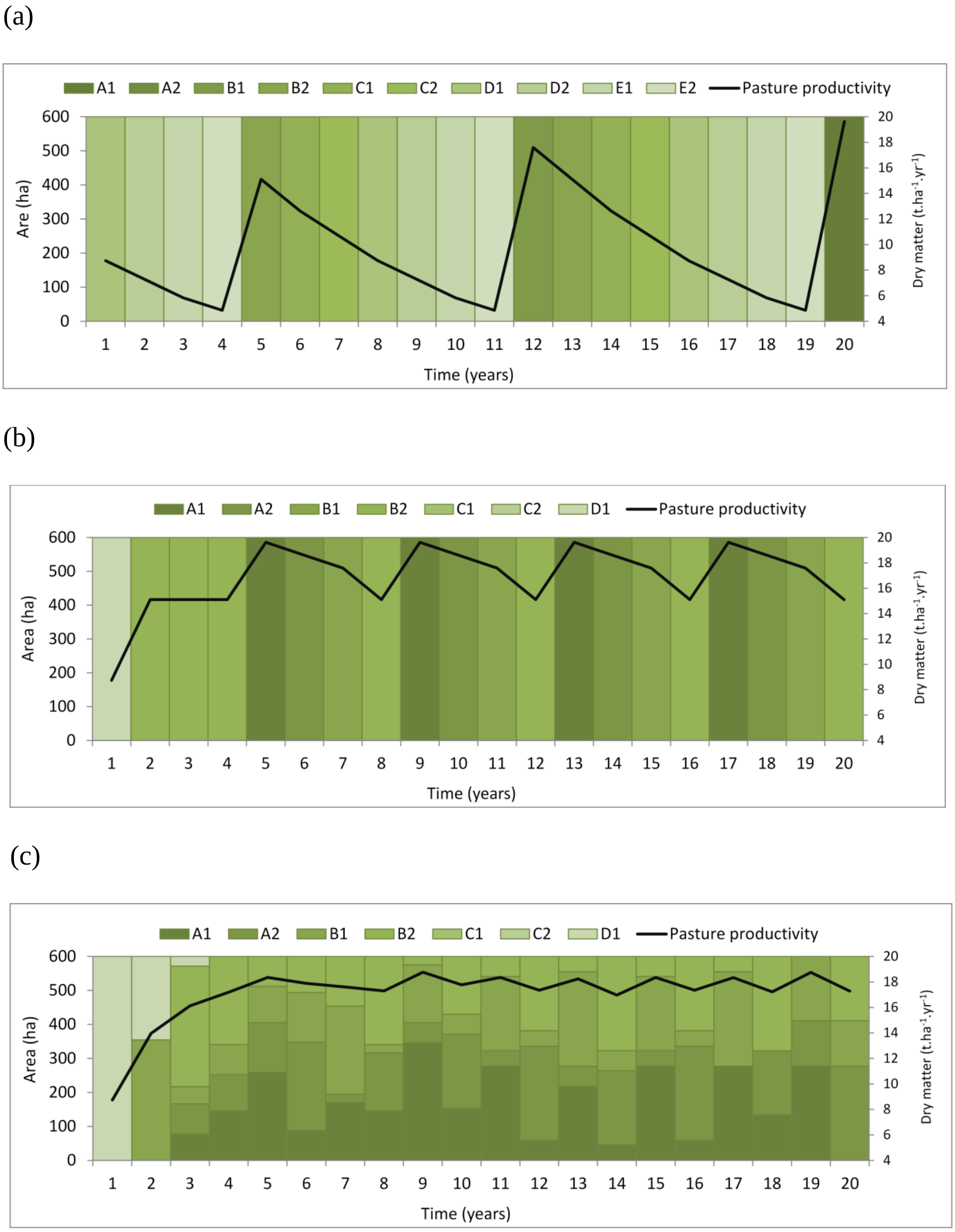


Figure 2: Pasture composition and associated forage productivity (a) TRP; (b) URP; and (c) FRP restoration practices under the LPP scenario.

Figures 3A-C shows that FRP has more consistent productivity, allowing for optimal relation between forage productivity and stocking rates over the production time. Fractionating pastures also require less cash inflow for investments, a barrier to the adoption of sustainable intensification measures (de Oliveira Silva et al., 2015; Moran et al., 2013)

In both FRP and URP the optimum level of productivity is around 18.3 t DM.ha^{-1}.yr^{-1}. Pasture degradation and restoration dynamics can cause SOC to switch from a sink to a source of CO_2 (Smith, 2014). Figure 3 shows TRP oscillates between losses and gains in SOC stocks, resulting in a slight increase from 45.2 to 47.2 tonnes of carbon per hectare (t-C.ha^{-1}), while SOC increased from 45.2 to 60.5 t-C.ha^{-1} for URP and FRP.

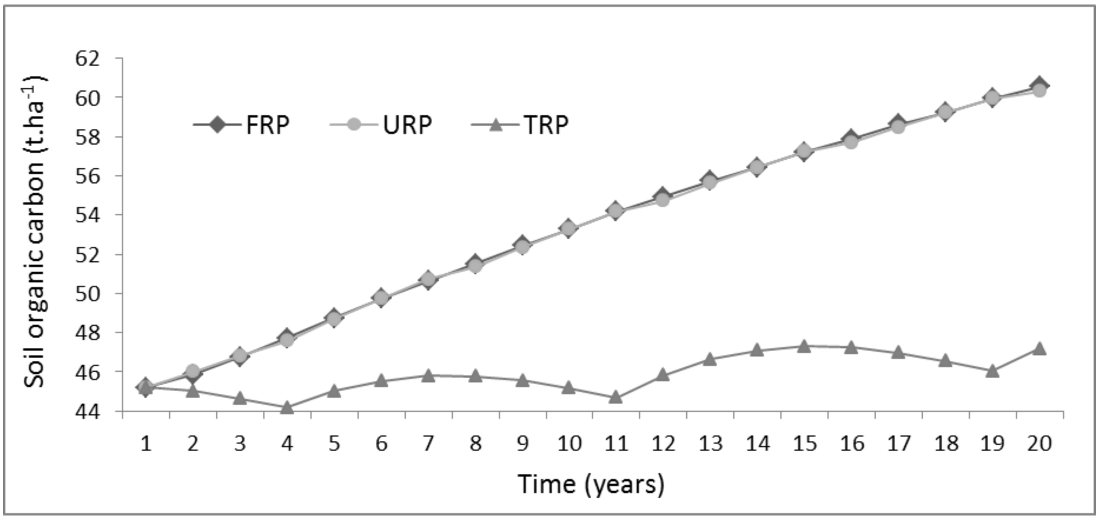


Figure 3: Soil organic carbon stocks as a function of time and restoration practices.

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

Figure 4 shows EI as an aggregation of the main GHG emissions sources from the stocking and finishing beef systems, i.e. excluded purchased calves related emissions. Emissions intensities were calculated with and without access to ABC credit under the LPP scenario. Due to the high initial level of degradation in the LPP scenario, even the TRP restoration means pastures are (moderately) intensified during the production period. Estimated EI is 11.50 kg CO_2-e/kg CWE.

Figure 4 shows that adopting the optimized pasture management practices could reduce these to around 3.59 kg CO_2-e/kg CWE, with emissions abatement resulting from SOC sequestration from improved grasses. Note that direct cattle emissions account for around 11.87 kg CO_2-e/kg CWE, whereas SOC sequestration abates 3.8 kgCO_2-e/kg CWE, or 30% of cattle EI under TRP. If FRP or URP is adopted, gains in SOC stocks could abate 80-85% of cattle direct emissions (CH_4 and N_2O).

(a) (b)

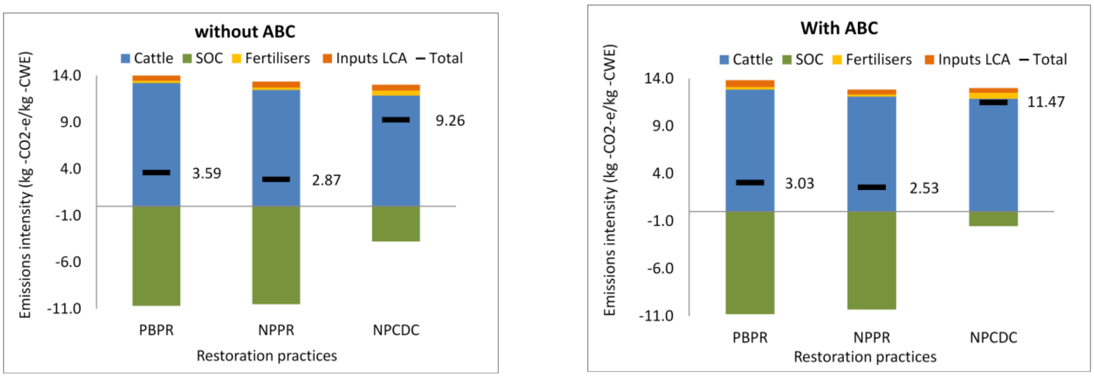
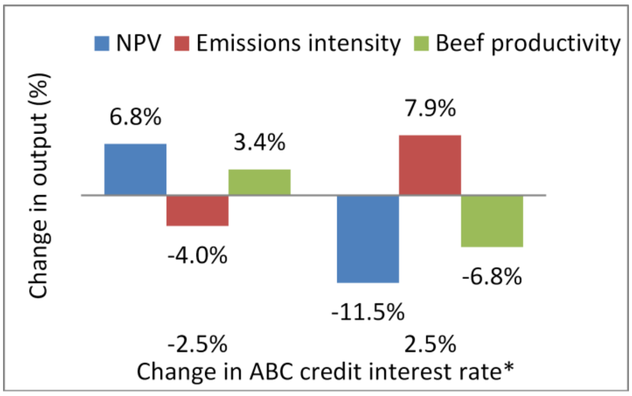


Figure 4: Emissions intensity comparison for the restoration practices under the LPP scenario without ABC credit (a) and with ABC credit (b). Emissions from cow-calf phase are not included.

On average, access to ABC credit reduces EI by around 20% when compared to the same pasture management practice, assuming that producers risk investing their own capital to optimally manage pastures in the scenario without ABC credit. This is because ABC credit provides more incentive for intensification (as seen in Fig. 1C-D), and SOC stocks are higher than without the credit.

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

Figure 5 shows a sensitivity analysis of ABC interest rates against NPV, emissions intensity and beef productivity for FRP.



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

Figure 5: Sensitivity analysis of ABC credit interest rate versus net present value, emissions intensity and beef productivity for FRP.

The NPV is highly sensitive to variations in the ABC interest rate. If the rate increases from the baseline value of 5.5% to 8% per year (p.y), NPV decreases by 11.5%, emissions intensity increases by around 8% and beef productivity decrease by around 7%. Reducing the interest rate to 3% p.y increases NPV and beef productivity by around 7% and 3.4%, respectively, while reducing emissions intensity by 4%.

4. Discussion

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

The farm level focus of this analysis means that we ultimately do not consider the extent to which systems intensification will influence deforestation rates through less extensive land use. Sparing land that could then be used for alternative production options clearly opens up the potential for other market mediated effects that could be just as extensive (Cohn et al., 2014; Gouvello et al., 2011). SAI technologies alone are unlikely to reduce land expansion if unaccompanied by targeted land management incentives and effective deforestation control policies (Arima et al., 2014).

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

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

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

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

5. Conclusion

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

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

Acknowledgments

We acknowledge funding from the UK Economic and Social Research Council (ESRC) under grant number ES/N013255/1. Rafael Silva acknowledges CAPES Foundation through the Science without Borders program for the scholarship no. 10180/13-3. Dominic Moran also acknowledges support from the N8 AgriFood programme at York, which is jointly funded by HEFCE and the N8 group of UK Universities

References

Anualpec, 2013. Anualpec : anuário da pecuária brasileira. São Paulo, São Paulo.

Arruda, Z.J. de., Corrêa, E.S., 1992. Avaliacao tecnico-economica de alternativa para o sistema fisico de producao de gado de corte do CNPGC: producao de novilho precoce, Comunicado Tecnico - Centro Nacional de Pesquisa de Gado de Corte (Brazil). no. 44. Campo Grande - MS.

Barioni, L.G., 2011. Embrapa Invernada [Computer Software]. Ver. 1.2.27.45 < http:// www.invernada.cnptia.embrapa.br> (accessed 11.05.2016)

Bisschop, J.M.R., 2011. AIMMS Language Reference. Paragon Decision Technology, Haarlem.

Brandão, M., Levasseur, A., Kirschbaum, M.U.F., Weidema, B.P., Cowie, A.L., Jørgensen, S.V., Hauschild, M.Z., Pennington, D.W., Chomkhamsri, K., 2013. Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. Int. J. Life Cycle Assess. 18, 230–240. doi:10.1007/s11367-012-0451-6

Brazil, 2015. Intended Nationaly Determined Contribution (INDCs) [WWW Document]. Libr. Congr. <http://www4.unfccc.int/submissions/INDC/Published Documents/Brazil/1/BRAZIL iNDC english FINAL.pdf>

Britz, W., Witzke, H.P., 2012. CAPRI model documentation 2012. <www. capri-model> org.

Cardoso, A.S., Berndt, A., Leytem, A., Alves, B.J.R., de Carvalho, I. das N.O., de Barros Soares, L.H., Urquiaga, S., Boddey, R.M., 2016. Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use. Agric. Syst. 143, 86–96. doi:10.1016/j.agsy.2015.12.007

Cederberg, C., Meyer, D., Flysjö, A., 2009. Life Cycle Inventory of Greenhouse Gas Emissions and Use of Land and Energy in Brazilian Beef Production. SIK-Institutet för Livsmedel och Bioteknik < https://www.diva-portal.org/smash/get/diva2:943348/FULLTEXT01.pdf > (accessed 17.02.2016)

Costa, F.P., Corrêa, E.S., Melo Filho, G.A. de, Cezar, I.M., Pereira, M. de A., 2005. Sistemas e custos de produção de gado de corte em Mato Grosso do Sul-regiões de Campo Grande e Dourados. Embrapa Gado de Corte, Campo Grande - MS.

CPLEX, I.B.M.I., 2009. V12. 1: User’s Manual for CPLEX. Int. Bus. Mach. Corp. 46, 157.

Crespoline dos Santos, M., 2015. As mudanças da bovinocultura de corte no Brasil : evidências a partir de Mato Grosso do Sul (2004 - 2015) [dissertation]. University of Campinas.

De Figueiredo, E.B., Jayasundara, S., de Oliveira Bordonal, R., Berchielli, T.T., Reis, R.A., Wagner-Riddle, C., La Scala, N., 2017. Greenhouse gas balance and carbon footprint of beef cattle in three contrasting pasture-management systems in Brazil. J. Clean. Prod. 142, 420–431. doi:10.1016/j.jclepro.2016.03.132

De Oliveira, O.C., De Oliveira, I.P., Alves, B.J.R., Urquiaga, S., Boddey, R.M., 2004. Chemical and biological indicators of decline/degradation of Brachiaria pastures in the Brazilian Cerrado. Agric. Ecosyst. Environ. 103, 289–300. doi:10.1016/j.agee.2003.12.004

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

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

Dent, J.B., Harrison, S.R., Woodford, K.B., 2013. Farm planning with linear programming: concept and practice. Elsevier.

Ecoinvent, 2014. <http://www.ecoinvent.ch> (acessed 05.04.2015)

Eggleston, S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., 2006. IPCC guidelines for national greenhouse gas inventories. Hayama, Japan.

FGV, 2012. General Price Index - Internal Availability <http://portalibre.fgv.br>

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. & Tempio, G., 2013. Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Rome.

Gouvello, C. de, Filho, B.S.S., Hissa, L., Nassar, A., Harfuch, L., Moreira, M.M.R., Luciane Chiodi, Antoniazzi, L.B., Antoniazzi, B.B., Barioni, L.G., Junior, G.M., Sainz, R.D., Alves, B.J.R., Lima, M.A. de, Martins, O., Branco, M.C., Toledo, R., Verde, M.R.L., Marques, F., Ferreira, R., Goulart, L., Mendes, T., Moreira, A., Farinelli, B., Chang, J.M., Pinto, R., Hato, J., Pacca, S., Freitas, S.R., Longo, K.M., Siqueira, R.A. de, 2011. Brazil Low Carbon Case study: Technical Synthesis Report. The World Bank Group, Washington,DC.

IEA, 2012. Survey of monthly average prices received by farmers <http://www.iea.sp.gov.br/out/bancodedados.html> (accessed 12.01.2014)

Lessa, A.C.R., Madari, B.E., Paredes, D.S., Boddey, R.M., Urquiaga, S., Jantalia, C.P., Alves, B.J.R., 2014. Bovine urine and dung deposited on Brazilian savannah pastures contribute differently to direct and indirect soil nitrous oxide emissions. Agric. Ecosyst. Environ. 190, 104–111. doi:10.1016/j.agee.2014.01.010

Loos, J., Abson, D.J., Chappell, M.J., Hanspach, J., Mikulcak, F., Tichit, M., Fischer, J., 2014. Putting meaning back into “sustainable intensification.” Front. Ecol. Environ. 12, 356–361. doi:10.1890/130157

Macedo, M.C.M., Zimmer, A.H., 1993. Sistema pasto-lavoura e seus efeitos na produtividade agropecuária. In: Simpósio sobre ecossistemas de pastagens 2, 216–245.

Macedo, M.C.M., Zimmer, A.H., Kichel, A.N., de Almeida, R.G., de Araújo, A.R., 2014. Degradação de pastagens, alternativas de recuperação e renovação, e formas de mitigação, in: Embrapa Gado de Corte-Artigo Em Anais de Congresso (ALICE). Ribeirão Preto, SP, pp. 158–181.

Maia, S.M.F., Ogle, S.M., Cerri, C.E.P., Cerri, C.C., 2009. Effect of grassland management on soil carbon sequestration in Rondônia and Mato Grosso states, Brazil. Geoderma 149, 84–91. doi:10.1016/j.geoderma.2008.11.023

Martha, G.B., Alves, E., Contini, E., 2012. Land-saving approaches and beef production growth in Brazil. Agric. Syst. 110, 173–177. doi:10.1016/j.agsy.2012.03.001

Moran, D., Lucas, A., Barnes, A., 2013. Mitigation win–win. Nat. Clim. Chang. 3, 611–613. doi:10.1038/nclimate1922

Mozzer, G.B., 2011. Agriculture and cattle raising in the context of a low carbon economy. In: Seroa da Motta, R. (Ed.), Climate Change in BrazilEconomic, Social and Regulatory Aspects. IPEA, Brasília, DF, p. 358

NATIONAL RESEARCH COUNCIL - NRC, 2000. Nutrients requeriments of beef cattle, 7th ed. National Academic Press, Washington, DC.

Parton, W.J., Schimel, D.S., Cole, C. V, Ojima, D.S., 1987. Analysis of Factors Controlling Soil Organic Matter Levels in Great Plains Grasslands1. Soil Sci. Soc. Am. J. 51, 1173. doi:10.2136/sssaj1987.03615995005100050015x

Peron, A.J., Evangelista, A.R., 2004. Degradação de pastagens em regiões de cerrado. Ciência e Agrotecnologia 28, 655–661.

Ruviaro, C.F., de Léis, C.M., Lampert, V. do N., Barcellos, J.O.J., Dewes, H., 2014. Carbon footprint in different beef production systems on a southern Brazilian farm: a case study. J. Clean. Prod. doi:10.1016/j.jclepro.2014.01.037

SimaPro Analyst, 2011. http://www.pre-sustainability.com/simapro (acessed 02.05.2015)

Smith, P., 2014. Do grasslands act as a perpetual sink for carbon? Glob. Chang. Biol. 20, 2708–2711. doi:10.1111/gcb.12561

SPRP, 2014. Pecuária verde: Produtividade, legalidade e bem-estar na fazenda. SPRP, Paragominhas.< http://www.pecuariasustentavel.org.br/wp-content/uploads/2014/05/1b9cb1_4400a5e3ba99430d8b763f57d4714426-1.pdf > (acessed 11.06.2016)

Strassburg, B.B.N., Latawiec, A.E., Barioni, L.G., Nobre, C.A., da Silva, V.P., Valentim, J.F., Vianna, M., Assad, E.D., 2014. When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. Glob. Environ. Chang. 28, 84–97. doi:10.1016/j.gloenvcha.2014.06.001

Tonato, F., Barioni, L.G., Silveira Pedreira, C.G., Dantas, O.D., Malaquias, J.V., 2010. Development of forage accumulation prediction models in tropical pastures. Pesqui. Agropecu. Bras. 45, 522–529. doi:10.1590/S0100-204X2010000500012

Vuichard, N., Ciais, P., Viovy, N., Calanca, P., Soussana, J.-F., 2007. Estimating the greenhouse gas fluxes of European grasslands with a process-based model: 2. Simulations at the continental level. Global Biogeochem. Cycles 21, n/a–n/a. doi:10.1029/2005GB002612

Weintraub, a., Romero, C., 2006. Operations Research Models and the Management of Agricultural and Forestry Resources: A Review and Comparison. Interfaces (Providence). 36, 446–457. doi:10.1287/inte.1060.0222

Xavier, D.F., da Silva Lédo, F.J., de Campos Paciullo, D.S., Urquiaga, S., Alves, B.J.R., Boddey, R.M., 2014. Nitrogen cycling in a Brachiaria-based silvopastoral system in the Atlantic forest region of Minas Gerais, Brazil. Nutr. Cycl. Agroecosystems 99, 45–62. doi:10.1007/s10705-014-9617-x

Supplementary information

Table S1: Parameters for emissions factors estimation

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

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