nature climate change

LETTERS

PUBLISHED ONLINE: 18 JANUARY 2016 | DOI: 10.1038/NCLIMATE2916

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

R. de Oliveira Silva[1,2*], L. G. Barioni[3], J. A. J. Hall[1], M. Folegatti Matsuura[4], T. Zanett Albertini[5], F. A. Fernandes[6] and D. Moran[2]

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

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

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

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

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

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

[1]School of Mathematics, The University of Edinburgh, Mayfield Road, Edinburgh EH9 3JZ, UK. [2]Research Division, SRUC, West Mains Road, Edinburgh EH9 3JG, UK. [3]Embrapa Agriculture Informatics, CEP 13083-886 Campinas-SP, Brazil. [4]Embrapa Environment, CEP: 13820-000 Jaguariúna-São Paulo, Brazil. [5]Luiz de Queiroz College of Agriculture, University of Sao Paulo (ESALQ/USP), CEP 13418-900, Piracicaba, São Paulo, Brazil. [6]Embrapa Pantanal, CEP 79320-900, Corumbá-Mato Grosso do Sul, Brazil. *e-mail: rafael.silva@sruc.ac.uk

Figure 1 | Brazilian central Cerrado (shaded).

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

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

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

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

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

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

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

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

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

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

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

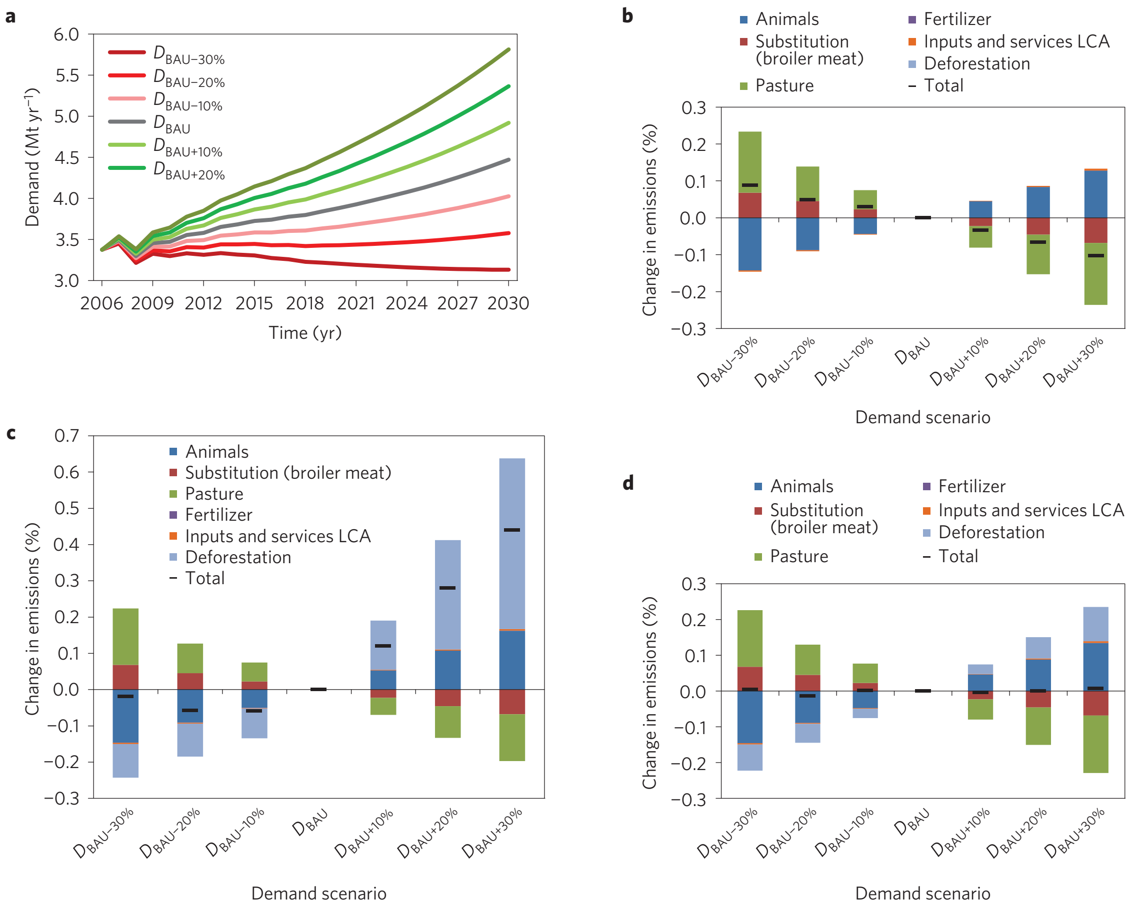

Figure 2 | Demand scenarios and sensitivity analysis. **a**, Cerrado baseline demand (D_{BAU}) and varied demand projections that correspond to percentage variation by 2030 in relation to D_{BAU}. **b–d**, Percentage changes in accumulated emissions (2006–2030) as a function of demand scenarios under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

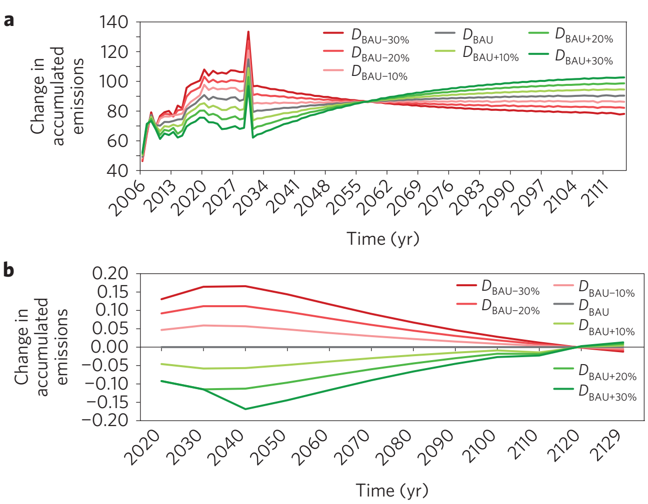

Figure 3 | Long-term GHG emissions analysis for the demand scenarios. **a**, Annual net GHG emissions. **b**, Percentage changes in accumulated GHGs. Note that the emissions peak in 2030 (**a**) is due to high deforestation rates in that year in the baseline projections employed[17].

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

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

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

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

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

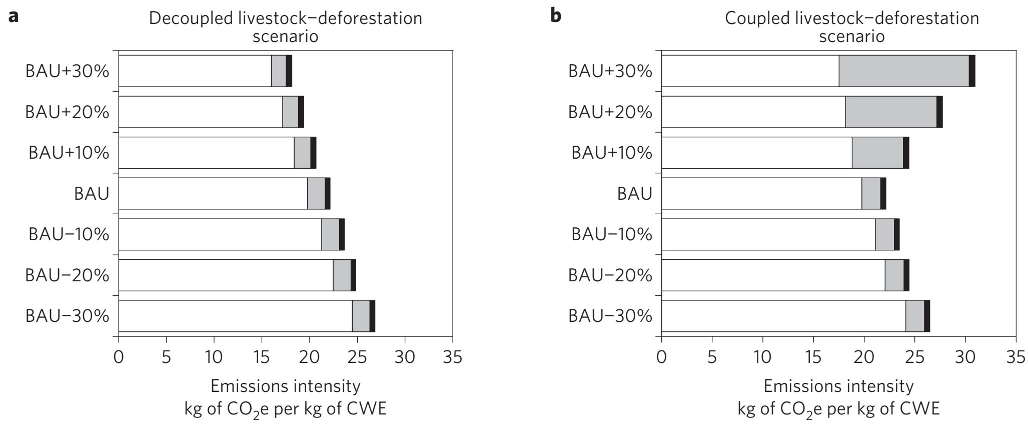

Figure 4 | Emissions intensity analysis. a, Emissions intensity as a function of demand scenario for the decoupled livestock–deforestation scenario. **b**, Emissions intensity as a function of demand scenario for the coupled livestock–deforestation scenario. Carbon footprint calculated as the average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

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

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

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

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

Methods

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

Received 2 October 2015; accepted 14 December 2015; published online 18 January 2016

References

1. Bajželj, B. *et al.* Importance of food-demand management for climate mitigation. *Nature Clim. Change* **4,** 924–929 (2014).
2. Tilman, D., Balzer, C., Hill, J. & Befort, B. L. Global food demand and the sustainable intensification of agriculture. *Proc. Natl Acad. Sci. USA* **108,** 20260–20264 (2011).
3. Garnett, T. *et al.* Agriculture. Sustainable intensification in agriculture: premises and policies. *Science* **341,** 33–34 (2013).
4. Herrero, M. *et al.* Smart investments in sustainable food production: revisiting mixed crop-livestock systems. *Science* **327,** 822–825 (2010).
5. Steinfeld, H. *et al. Livestock's Long Shadow* Vol. 3 (Organization, 2006).
6. Herrero, M., Thornton, P. K., Gerber, P. & Reid, R. S. Livestock, livelihoods and the environment: understanding the trade-offs. *Curr. Opin. Environ. Sustain.* **1,** 111–120 (2009).
7. Smith, P. Delivering food security without increasing pressure on land. *Glob. Food Secur.* **2,** 18–23 (2013).
8. Godfray, H. C. J. *et al.* Food security: the challenge of feeding 9 billion people. *Science* **327,** 812–818 (2010).
9. Soussana, J. F., Tallec, T. & Blanfort, V. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. *Animal* **4,** 334–350 (2010).
10. FAOStat (FAO, accessed 15 January 2015); http://faostat3.fao.org/browse/Q/QL/E
11. Brazilian Institute of Geography and Statistics *Censo Agropecuário 2006* (2006 Agricultural Census) (Instituto Brasileiro de Geografia e Estatítisca (IBGE), accessed 5 June 2015); http://www.sidra.ibge.gov.br/bda/acervo/acervo2.asp
12. Brazilian agriculture: the miracle of the Cerrado. *The Economist* (26 August 2010); http://www.economist.com/node/16886442
13. Rohter, L. Scientists are making Brazil's savannah bloom. *The New York Times* (2 October 2007); http://www.nytimes.com/2007/10/02/science/02tropic.html?pagewanted=all&_r=0
14. Maia, S. M. F., Ogle, S. M., Cerri, C. E. P. & Cerri, C. C. Effect of grassland management on soil carbon sequestration in Rondônia and Mato Grosso states, Brazil. *Geoderma* **149,** 84–91 (2009).
15. Braz, S. P. *et al.* Soil carbon stocks under productive and degraded pastures in the Brazilian Cerrado. *Soil Sci. Soc. Am. J.* **77,** 914–928 (2013).
16. Eggleston, S., Buendia, L., Miwa, K., Ngara, T. & Tanabe, K. *2006 IPCC Guidelines for National Greenhouse Gas Inventories* Vol. 4 (IPCC, 2006); http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html
17. De Gouvello, C. *et al. Brazil Low-Carbon Country Case Study* (World Bank Group, 2010); http://siteresources.worldbank.org/BRAZILEXTN/Resources/Brazil_LowcarbonStudy.pdf
18. Smith, P. Do grasslands act as a perpetual sink for carbon? *Glob. Change Biol.* **20,** 2708–2711 (2014).
19. Johnston, A. E., Poulton, P. R. & Coleman, K. Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. *Adv. Agron.* **101,** 1–57 (2009).
20. Cerri, C. E. P. *et al.* Simulating SOC changes in 11 land use change chronosequences from the Brazilian Amazon with RothC and Century models. *Agric. Ecosyst. Environ.* **122,** 46–57 (2007).
21. Lapola, D. M. *et al.* Pervasive transition of the Brazilian land-use system. *Nature Clim. Change* **4,** 27–35 (2014).
22. Nepstad, D. *et al.* Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science* **344,** 1118–1123 (2014).
23. Macedo, M. N. *et al.* Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. *Proc. Natl Acad. Sci. USA* **109,** 1341–1346 (2012).
24. Strassburg, B. B. N. *et al.* When enough should be enough: improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. *Glob. Environ. Change* **28,** 84–97 (2014).
25. Mozzer, G. B. in *Climate Change in Brazil: Economic, Social and Regulatory Aspects* (ed. Seroa da Motta, R.) Ch. 6 (IPEA, 2011); https://www.ipea.gov.br/agencia/images/stories/PDFs/livros/livro/livro_climatechange_ingles.pdf#page=108
26. Hedenus, F., Wirsenius, S. & Johansson, D. A. The importance of reduced meat and dairy consumption for meeting stringent climate change targets. *Climatic Change* **124,** 1–13 (2014).
27. Rada, N. Assessing Brazil's Cerrado agricultural miracle. *Food Policy* **38,** 146–155 (2013).

Acknowledgements

We acknowledge financial support from the EU FP7 project AnimalChange under the grant agreement no. 266018. R.d.O.S. acknowledges the CAPES Foundation for the scholarship no. 10180/13-3. D.M. acknowledges financial support from the Scottish Government Rural and Environmental Science and Analytical Services division through ClimatexChange (http://www.climatexchange.org.uk).

Author contributions

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

Additional information

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

Competing financial interests

The authors declare no competing financial interests.

Methods

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

GHG emissions sources. EAGGLE estimates GHGs using emissions factors for direct emissions and life-cycle assessment (LCA). GHG emissions associated with farm activities are: (a) CH_4 from cattle enteric fermentation (CH_4 from excreta is not accounted); (b) N_2O from cattle excreta; (c) N_2O from N fertilization conversion; (d) CO_2 from Cerrado deforestation (due to loss of natural vegetation); (e) CO_2 from pasture degradation and land use change from pasture to crops; and (f) LCA factors for inputs and farm operations applied in land use change and restoration practices (Supplementary Table 2). Items (a) and (b) depend on herd composition: each age cohort of males and females (heifer or cow) has an associated emission factor of CH_4 and N_2O calculated using Tier 2 methodology[16] (see values in Supplementary Table 1). Owing to the lack of studies for Brazilian conditions, for (c) we used the Tier 1 Intergovernmental Panel on Climate Change default factor of 1% (ref. 16). The emissions from (d) are calculated using a coefficient of loss of natural vegetation per hectare of deforested area, estimated as 34.6 tons of C per hectare[28]. For (e), the emissions are calculated according to the section Soil organic carbon dynamics (Supplementary Methods).

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

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

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

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

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

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

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

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

References

28. Bustamante, M. M. C. *et al.* Estimating greenhouse gas emissions from cattle raising in Brazil. *Climatic Change* **115,** 559–577 (2012).
29. Parton, W. J., Schimel, D. S., Cole, C. V. & Ojima, D. S. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Sci. Soc. Am. J.* **51,** 1173–1179 (1987).