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

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1 <http://www.nature.com/nclimate/journal/vaop/ncurrent/full/nclimate2916.html>  
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3 **Increasing beef production could lower greenhouse gas emissions in Brazil if**  
4 **decoupled from deforestation**

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7

8 Recent debate about agricultural greenhouse gases (GHG) emissions mitigation highlights trade-  
9 offs inherent in the way we produce and consume food, with increasing scrutiny on emissions-  
10 intensive livestock products<sup>1-3</sup>. While most research has focussed on mitigation through  
11 improved productivity<sup>4,5</sup>, systemic interactions resulting from reduced beef production at  
12 regional level are still unexplored. A detailed optimisation model of beef production  
13 encompassing pasture degradation and recovery processes, animal and deforestation emissions,  
14 soil organic carbon (SOC) dynamics and upstream lifecycle inventory was developed and  
15 parameterized for the Brazilian *Cerrado*. Economic return was maximized considering two  
16 alternative scenarios: Decoupled Livestock Deforestation (DLD), assuming baseline  
17 deforestation rates controlled by effective policy; and Coupled Livestock Deforestation (CLD),  
18 where shifting beef demand alters deforestation rates. In DLD, reduced consumption actually  
19 leads to less productive beef systems, associated with higher emissions intensities and total  
20 emissions, while increased production leads to more efficient systems with boosted SOC stocks,  
21 reducing both per kg and total emissions. Under CLD, increased production leads to 60% higher  
22 emissions than in DLD. The results indicate the extent to which deforestation control contributes  
23 to sustainable intensification in *Cerrado* beef systems, and how alternative life-cycle analytical  
24 approaches<sup>6</sup> result in significantly different emission estimates.

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29           Rising global population combined with shifting dietary preferences in emerging  
30 economies are leading to a significant increase in demand for livestock products, which is  
31 expected to double by 2050<sup>2</sup>. This shift is happening in the context of global climate change and  
32 associated resource scarcities, leading to calls for sustainable agricultural intensification (SI)<sup>3,5,7</sup>.  
33 Although a contested concept, the SI debate highlights elements of resource use efficiency in  
34 production, combined with the management of demand or consumption<sup>3,8,9</sup>. While persuasive,  
35 the SI literature is limited in its illustration of the environmental and economic trade-offs that can  
36 emerge when implementing SI measures in globally significant production systems.

37           Ruminant livestock is specifically implicated as a major cause of agricultural externalities  
38 in terms of GHG emissions (CH<sub>4</sub> and N<sub>2</sub>O) and appropriation of land that otherwise provisions  
39 valuable ecosystem services<sup>5</sup>. A counter-argument suggests grass-fed beef systems have  
40 significantly lower emissions when accounting for atmospheric carbon dioxide (CO<sub>2</sub>) uptake by  
41 deep-root grasses promoting greater soil carbon (C) storage. Such systems could play a  
42 significant role in stabilising GHGs<sup>10</sup>. Moreover this sequestration in specific systems may off-  
43 set direct livestock emissions<sup>10</sup>.

44           Brazilian livestock production accounts for 8.3% of global consumption<sup>11</sup> and the sector  
45 aims to capitalise on growing demand. But related emissions are significant in the national GHG  
46 total including those related to deforestation. If both beef demand and target deforestation rates  
47 are to be met, while also reaching ambitious GHG mitigation targets, further productivity growth  
48 will be required. Alternatively product demand or consumption may need to be managed<sup>3,8</sup>.

49           This study focuses on the central savannah (*Cerrado*) core (Fig. 1), an area accounting  
50 for approximately 34% of Brazilian beef production<sup>12</sup>. Considered part of the Brazilian  
51 agricultural frontier, the *Cerrado* is credited as the driver of the country's ascendance in global

52 agricultural commodity markets<sup>13,14</sup>. Around 90% of Brazilian livestock are solely grass-fed  
53 (mainly tropical grasses of genus *Brachiaria*). Several studies show that improving tropical  
54 grasses productivity results in increased soil carbon stocks<sup>15,16</sup>, with net atmospheric CO<sub>2</sub>  
55 removals of almost 1 Mg C ha<sup>-1</sup>yr<sup>-1</sup> (ref. 15) when comparing degraded and improved pastures  
56 under a standard IPCC method<sup>17</sup>.

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59 Figure 1: Brazilian Central *Cerrado* (shaded).

60

61 The analysis quantifies the relationship between beef demand, production intensification,  
62 deforestation and soil carbon dynamics, indicating how deforestation rates influence emission  
63 intensities. We employed a linear programming model (**Methods** and **Supplementary Methods**)  
64 representing *Cerrado* beef production subject to market demand and pasture area scenarios. The  
65 model combines economic and bio economic variables to optimise farm resource allocation,  
66 including the adjustment of intensification levels through the representation of pasture

67 degradation and restoration processes. It estimates GHG emissions - including direct animal  
68 emissions (**Supplementary Table 1**), changes in SOC, plus loss of biomass through  
69 deforestation, and life-cycle assessment (LCA) data covering inputs and farm operations used to  
70 maintain and recover pasture, and crop production, the latter used to formulate animal feedlot  
71 rations (**Supplementary Table 2**).

72 As there is no published biome-specific beef demand projections in Brazil, baseline  
73 demand ( $D_{BAU}$ ) is assumed to be proportional to the whole country projected demand, i.e.  
74 exports plus domestic consumption<sup>18</sup>.

75 We compared the accumulated emissions 2006-2030 under two land use scenarios: the  
76 Decoupled Livestock-Deforestation (DLD) scenario, where the same baseline pasture area  
77 projection ( $A_{BAU}$ ) associated with the baseline demand is used for all demand scenarios; i.e., the  
78 same deforestation projections irrespective of consumption levels; and the Coupled Livestock-  
79 Deforestation (CLD) scenario, in which deforestation projections are sensitive to variations in  
80 demand. In both scenarios, intensification occurs only by pasture restoration promoting  
81 improvements in forage productivity through mechanical and chemical treatment of the soil  
82 (**Supplementary methods**).

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

86 Deforestation is assumed exogenous, avoiding the need to model competition between  
87 livestock and agricultural land use explicitly. To explore the link between beef demand and  
88 deforestation we use a parameter ( $k$ ) to represent the percentage variation of pasture area in  
89 relation to changes in demand. Based on empirical evidence<sup>11,12</sup> estimated  $k$  values decreased

90 from over 0.4 in the early 1970's to zero in the latest available data period (1995-2006), see  
91 **Supplementary file**. In the CLD scenario we assume the worst case  $k = 0.4$ , i.e., for every 1%  
92 variation in demand, pasture area changes by 0.4%, which would generate a deforested area of  
93 10.9 Mha by 2030 relative to 1.5 Mha for the baseline projections (**Supplementary Table 3**).

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

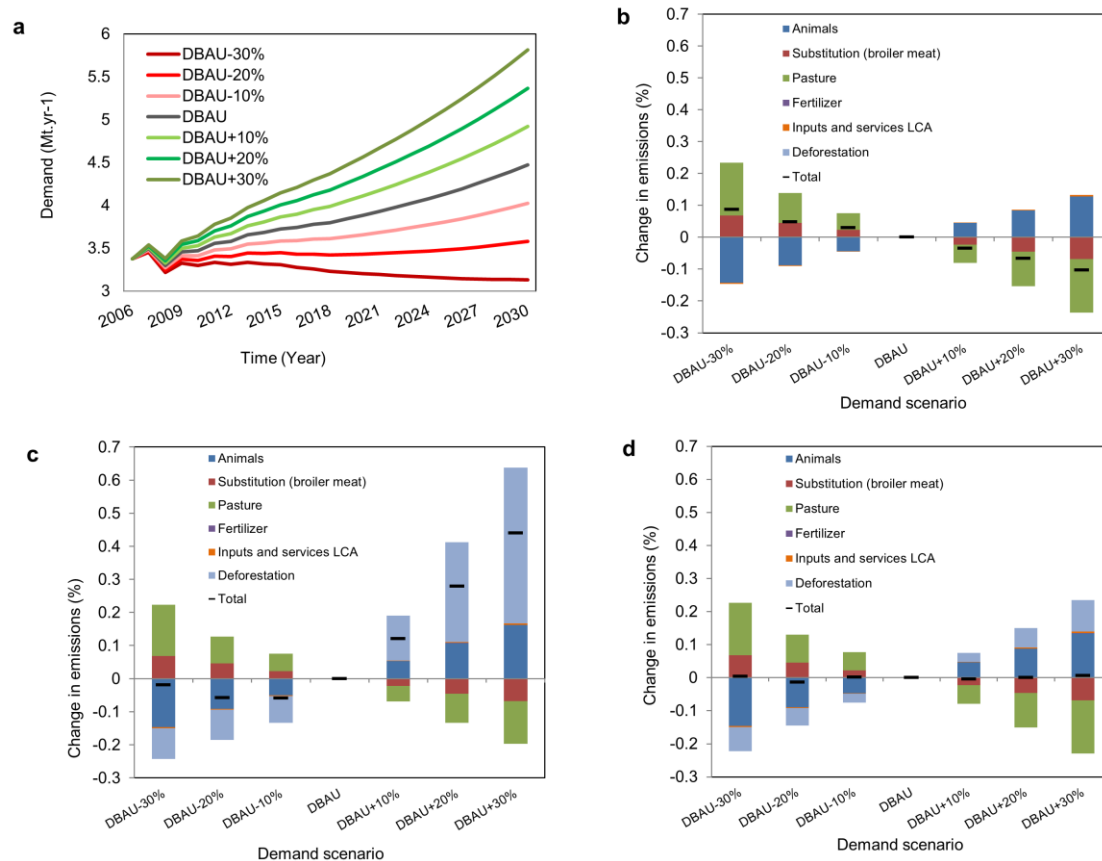
102 Under DLD, emissions increase by 3%, 5% and 9%, respectively for the consumption  
103 reduction scenarios  $D_{BAU-10\%}$ ,  $D_{BAU-20\%}$  and  $D_{BAU-30\%}$ . But in  $D_{BAU+10\%}$ ,  $D_{BAU+20\%}$  and  $D_{BAU+30\%}$ ,  
104 emissions decrease by 3%, 7% and 10%, respectively relative to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

110 But this result is undermined by altering the deforestation scenarios. Under CLD and assuming  
111 pasture expansion responds to changes in demand as in the 1970's, accumulated emissions  
112 (2006-2030) from beef production would range from 2.1 Gt to 3.0 Gt of CO<sub>2</sub>-e, respectively for

113  $D_{\text{BAU-30\%}}$  and  $D_{\text{BAU+30\%}}$ , i.e., emissions would be 60% higher than in DLD for the same demand  
114 scenario  $D_{\text{BAU+30\%}}$ . The analysis shows that under both  $D_{\text{BAU-10\%}}$  and  $D_{\text{BAU-20\%}}$ , emissions  
115 decrease by 6%. Under  $D_{\text{BAU-30\%}}$  scenario emissions are reduced by 2%, relative to  $D_{\text{BAU}}$ . Under  
116  $D_{\text{BAU+10\%}}$ ,  $D_{\text{BAU+20\%}}$  and  $D_{\text{BAU+30\%}}$ , emissions increase 12%, 28% and 44%, relative to  $D_{\text{BAU}}$  (Fig.  
117 2c). The changes are mainly due to direct animal emissions and deforestation. Note that the  
118 increasing demand scenarios drive proportional increases in deforestation, but under decreasing  
119 demand scenarios deforestation cannot be less than zero. In fact for  $D_{\text{BAU-30\%}}$ ,  $D_{\text{BAU-20\%}}$  and  $D_{\text{BAU-10\%}}$ ,  
120 deforestation rates are insignificant in relation to baseline figures, making GHG reductions  
121 more modest for these scenarios relative to the increases driven by deforestation under increasing  
122 demand scenarios.

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

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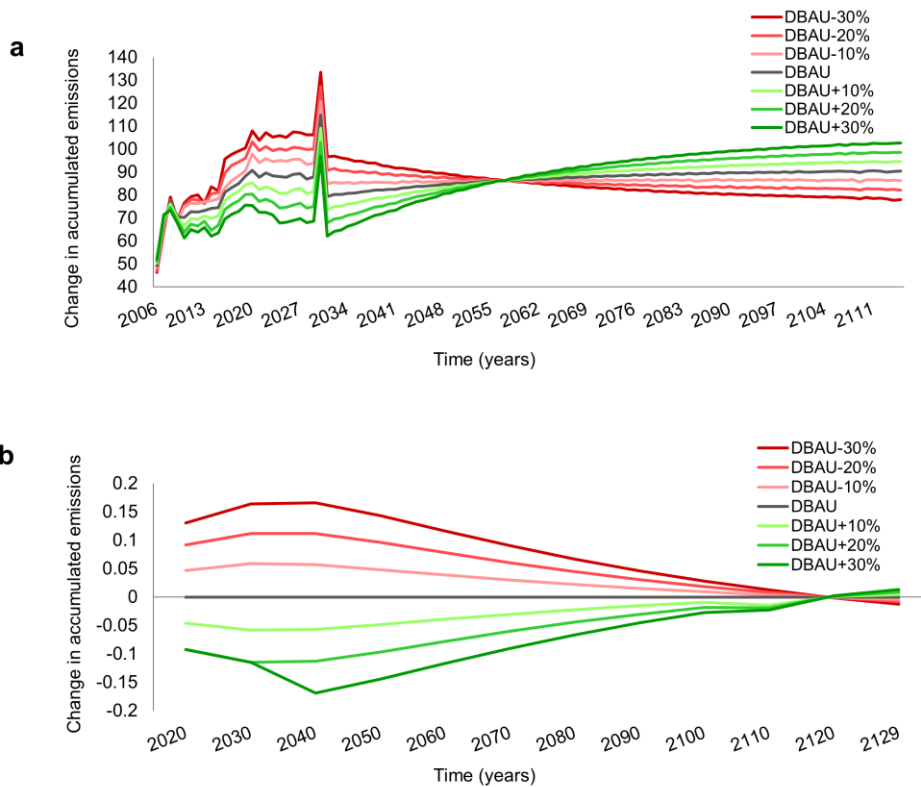
Figure 2: Demand scenarios and sensitivity analysis. **a**, *Cerrado* baseline demand ( $D_{BAU}$ ) and varied demand projections that correspond to percentage variation by 2030 in relation to  $D_{BAU}$ , **b**, percentage changes in accumulated emissions (2006-2030) as a function of demand scenarios under the DLD scenario, **c**, changes under the CLD scenario, **d**, changes for  $k=0.1$ . 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.

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<sup>19</sup>. To estimate the longevity of the inverse demand – emissions relationship (when SOC stocks approaches equilibrium content and no longer offset increased animal emissions), we conducted long-term



141 analysis for 125 years. Assuming fixed demand from 2030 to 2130 and observing: a) the annual  
142 net emissions and b) the changes in accumulated emissions in 10 year periods from 2010 for  
143 each demand scenario under DLD. As demand projections increase up to 2030, the assumption  
144 of constant demand and area from 2030 leads to stabilized land productivity from 2030 to 2130.

145 Under the DLD scenario, increases in demand would lead to decreases in annual  
146 emissions up to 2057, when the situation inverts (Fig. 3a). But Fig. 3b shows that in terms of  
147 accumulated emissions, reducing beef consumption would lead to decreased emissions around  
148 2120.

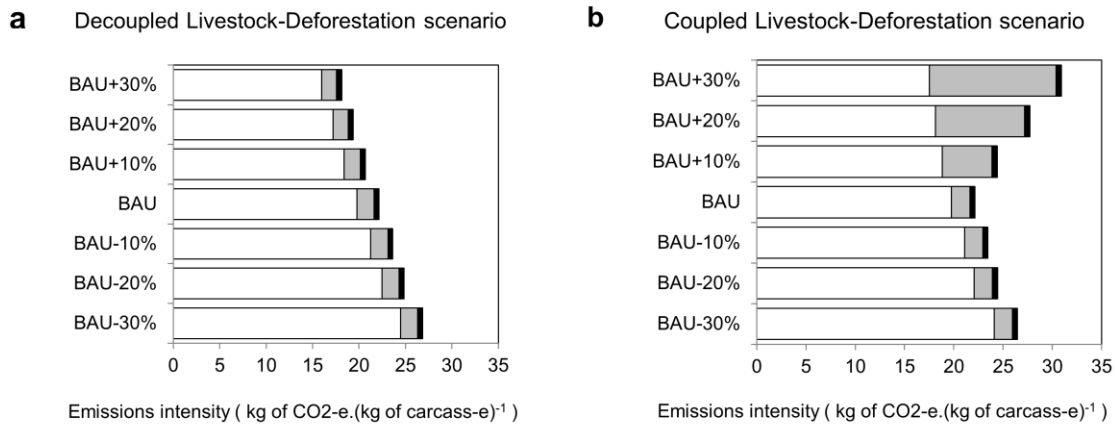


149  
150 Figure 3: Long term GHG emissions analysis for the demand scenarios. **a**, annual net GHG emissions. **b**,  
151 percentage changes in accumulated GHGs. Note that the emissions peak in 2030 (Fig. 3a) is due to high  
152 deforestation rates in that year in the baseline projections employed<sup>18</sup>

153           Although SOC equilibrium has not been reached by 2057, the average sequestration rate  
154 of 0.08t of C.ha<sup>-1</sup>.yr<sup>-1</sup> (under D<sub>BAU+30%</sub>) no longer offsets emissions from increased animal  
155 numbers. By 2057 SOC stocks reaches 60% of the difference between initial stocks and  
156 equilibrium values (**Supplementary Table 6**), i.e., 27 years after land productivity is stabilized,  
157 which is consistent with experimental evidence<sup>20-22</sup>.

158           Our results implicitly show significant changes in emissions intensity depending on  
159 demand scenarios and deforestation. The lowest value (18.1 kg of CO<sub>2</sub>-e/ kg of carcass  
160 equivalent (carcass-e) is observed under DLD and D<sub>BAU+30%</sub>, which uses the least area to produce  
161 most beef (Fig. 4a). Under the CLD scenario, the lowest value is found in the baseline demand  
162 (22.2 kg of CO<sub>2</sub>-e/ kg of carcass-e), while emissions intensity could reach 31.0 kg of CO<sub>2</sub>-e/ kg  
163 of carcass-e under D<sub>BAU+30%</sub> , around 40% of this being due to deforestation (Fig. 4b).

164



165

166 Figure 4: Emissions intensity as a function of demand scenario for **a**, Decoupled Livestock-Deforestation and **b**,  
 167 Coupled Livestock-Deforestation land use scenarios. Carbon footprint calculated as the average value from 2010 to  
 168 2025, showing the sum of farm-emissions: animals and pasture (emissions by degradation or carbon sequestration  
 169 and nitrogen fertilizers nitrification) (white), deforestation emissions (grey) and LCA emissions from inputs and  
 170 farm operations used to restore pastures and changed land use (e.g., fertilisers, seeds, and machinery operations)  
 171 (black).

172

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

176

177 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

178 that lower than projected beef demand may increase emissions in the *Cerrado* grazing system  
179 due to comparatively higher emission intensities.

180 Empirical evidence supports the DLD scenario by showing a calibrated value of  $k=0$  (see  
181 **Supplementary file**). Since 2005, data show an apparent decoupling of cattle herd sizes and  
182 deforestation in Amazonia and *Cerrado*, replacing an historic correlation over the period 1975-  
183 2005; a trend attributed to a combination of supply and demand side factors including  
184 intensification in large-scale commodity-oriented farming, market regulation (e.g. moratoria on  
185 beef and soy grown in recently opened areas), product certification, and more effective law  
186 enforcement<sup>23-25</sup>.

187 Recent studies indicate that current global trends in livestock productivity will not  
188 accommodate future projected global demand<sup>1</sup>. But this result adds to evidence that Brazil in  
189 particular has enough land to meet demand for food and energy at least until 2040 without  
190 further natural habitat conversion<sup>18,26</sup>. In fact under DLD the highest average stocking rate in the  
191 model, 1.33 head.ha<sup>-1</sup> (under D<sub>BAU+30%</sub>), is below the 2 head.ha<sup>-1</sup> carrying capacity associated  
192 with negative climate impacts<sup>26</sup>.

193 The analysis also indicates that restoration of degraded pastures is the biggest opportunity  
194 for national mitigation plans; indeed, after avoided deforestation, the restoration of 15 Mha  
195 nationwide from 2010 to 2020 is the main measure contributing to the 40% reduction target by  
196 2020 (ref. 27).

197 Because the analysis employs consequential LCA approach<sup>6</sup>, it contrasts to other  
198 results<sup>1,2,28</sup> using attributional analysis based on constant emission intensity irrespective of  
199 consumption level.

200 More generally our results reflect *Cerrado* system-specific data, and the picture might  
201 differ if we analyse other regions of Brazil or worldwide. The *Cerrado* is nevertheless seen as  
202 model for transforming other global savannahs<sup>29</sup>.

203

## 204 **Methods**

### 205 **EAGGLE model.**

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

212

### 213 **GHG emissions sources**

214 EAGGLE estimates GHG's using emissions factors for direct emissions and Life-Cycle  
215 Assessment (LCA). GHG emissions associated with farm activities are: (a) CH<sub>4</sub> from cattle  
216 enteric fermentation (CH<sub>4</sub> from excreta is not accounted); (b) N<sub>2</sub>O from cattle excreta; (c) N<sub>2</sub>O  
217 from N fertilisation conversion; (d) CO<sub>2</sub> from *Cerrado* deforestation (due to loss of natural  
218 vegetation); (e) CO<sub>2</sub> from pasture degradation and land use change from pasture to crops; and (f)  
219 LCA factors for inputs and farm operations applied in land use change and restoration practises  
220 (**Supplementary Table 2**). Items (a) and (b) depend on herd composition: each age cohort of

221 males and females (heifer or cow) has an associated emission factor of CH<sub>4</sub> and N<sub>2</sub>O calculated  
222 using Tier 2 methodology<sup>17</sup>, see values in **Supplementary Table 1**. Due to the lack of studies  
223 for Brazilian conditions, for (c) we used the Tier 1 IPCC default factor of 1%<sup>17</sup>. The emissions  
224 from (d) are calculated using a coefficient of loss of natural vegetation per hectare of deforested  
225 area, estimated as 34.6 tons of C per hectare<sup>30</sup>. For (e), the emissions are calculated according to  
226 equations (1) and (2) in section **Soil carbon stocks**.

227

## 228 **Soil carbon stocks**

229         Depending on the dry matter productivity (DMP) level, the C flux may change  
230 significantly. The EAGGLE model works with equilibrium values of the C stock for each type of  
231 pasture and crops. The higher the pasture productivity, the higher the C equilibrium value (See  
232 **Supplementary Table 4**). Equilibrium values and the time to reach equilibrium were calculated  
233 exogenously, using simulations from the CENTURY model<sup>31</sup> applied to *Cerrado* biophysical  
234 characteristics and using the annual DMP calculated for each pasture category.

235

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## 238 **Demand and pasture area data**

239         Projections from The World Bank<sup>18</sup> were used for both pasture area and beef demand.  
240 The projections correspond to the period 2006-2030. Historical data 2006-2013 were used to  
241 validate the employed demand projections (**Supplementary file**). For pasture area projections,  
242 the last observational data was in 2006 (last agricultural census).

243 We assume *Cerrado* pasture area and beef demand share are a fixed proportion of the  
 244 national projections - since there is no biome- specific predictions in the literature. The *Cerrado*  
 245 pasture area represented around 34% of the national total in 2006 (when the last agricultural  
 246 census<sup>12</sup> was undertaken). We therefore assume *Cerrado* pasture area corresponds to 34% of  
 247 Brazil's pasture area projections, and that this proportion is constant during the study period  
 248 (2006-2030). Similarly, we assume beef demand to be proportional to area, thus demand for  
 249 *Cerrado* output is also equivalent to 34% of national demand. The model is partial with  
 250 comparative static equilibrium adjustment between demand and supply; i.e., each year,  
 251 production equals demand and prices remain constant for the whole period

252

### 253 **Scenario construction and deforestation**

254 In both Coupled Livestock-Deforestation and Decoupled Livestock-Deforestation  
 255 scenarios, pasture area and therefore deforestation is exogenous to the optimisation model.

256 The analysis employs baseline pasture area projections from a World Bank study<sup>18</sup>. For  
 257 the CLD scenario, we estimate changes in deforestation as a function of changes in beef demand  
 258 by assuming that for every change in annual demand in relation to baseline projections would  
 259 cause a proportional change in annual pasture area:

$$260 \quad \frac{A_{BAU+X\%,t} - A_{BAU,t}}{A_{BAU,t}} = k \frac{D_{BAU+X\%,t} - D_{BAU}}{D_{BAU}} \Rightarrow A_{BAU+X\%,t} = \left[ 1 + k \left( \frac{D_{BAU+X\%,t}}{D_{BAU,t}} - 1 \right) \right] A_{BAU,t}$$

261 Where  $A_{BAU+X\%,t}$  represents the altered pasture area projections in relation to baseline  
 262 projections  $A_{BAU,t}$ ;  $D_{BAU+X\%}$  represents the altered demand projection where  $X$  is in [-30,-20,-

263 10,10,20,30] and represents the change by 2030;  $D_{BAU}$  the baseline demand;  $k$  is the proportional  
264 change in pasture area due to changes in demand projections.

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

267

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354 **Contributions**

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

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