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1 **Developing a Nationally Appropriate Mitigation Measure from the**
2 **greenhouse gas GHG abatement potential from livestock production in**
3 **the Brazilian Cerrado**

4

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28

29 **Abstract**

30

31 Brazil is one of the first major developing countries to commit to a national
32 greenhouse gas (GHG) emissions target that requires a reduction of between
33 36.1% and 38.9% relative to baseline emissions by 2020. The country
34 intends to submit agricultural emissions reductions as part of this target,
35 with livestock production identified as offering significant abatement
36 potential. Focusing on the *Cerrado* core (central Brazilian savannah), this
37 paper investigates the cost-effectiveness of this potential, which involves
38 some consideration of both the private and social costs and benefits (e.g.
39 including avoided deforestation) arising from specific mitigation measures
40 that may form part of Brazil's definition of Nationally Appropriate
41 Mitigation Measures (NAMAs). The analysis used an optimization model
42 to define abatement costs. A baseline projection suggests that beef
43 production in the region will emit 2.6 Gt CO₂e (CO₂ equivalent) from 2010
44 to 2030, corresponding to 9% of national emissions (including energy,
45 transport, waste, livestock and agriculture). By implementing negative-cost
46 measures identified in a marginal abatement cost curve (MACC) by 2030,
47 the 2.6 Gt CO₂e could be reduced by around 24%. Pasture restoration,
48 involving avoided deforestation, offers the largest contribution to these
49 results. As the Brazilian *Cerrado* is seen as model for transforming other
50 global savannahs, the results offer a significant contribution by identifying
51 alternatives for increasing productivity whilst minimizing national and
52 global external costs.

53

54 **Keywords:** climate change; marginal abatement cost curves; mitigation
55 measures; sustainable intensification; grassland restoration; linear
56 programming.

57

58

59 **Highlights**

- 60 • Around 66% of beef production emissions in the *Cerrado* are due
61 to enteric fermentation.
- 62 • 24% of emissions can be reduced by adopting negative-cost (cost-
63 saving) measures.
- 64 • Pasture restoration has the biggest abatement potential (27.8 Mt
65 CO₂e.yr⁻¹).

66

67 **1. Introduction**

68

69 Global demand for livestock products is projected to grow by 70%
70 by 2050 (Gerber et al., 2013). This is expected to generate significant
71 additional pressure on producers and on natural resources. Sustainable
72 management (or intensification) will require increasing yields and efficiency
73 in existing ruminant production systems, minimizing competition of land
74 used for food and feed, while maximizing ecosystem services, including
75 mitigation of greenhouse gas (GHG) emissions (Gerber et al., 2013;
76 Soussana et al., 2013; Thornton and Herrero, 2010).

77 Tropical regions are implicated as potentially offering major
78 opportunities to increase beef productivity and emissions mitigation, as
79 current productivity levels are still relatively low and emission intensities
80 correspondingly high (Opio et al., 2013; Gerber et al., 2013).

81 More productive pastures can increase soil carbon stocks,
82 providing one of the largest terrestrial carbon sinks (Follett and Reed, 2010;
83 Neely et al., 2009), in a pool that is a more stable form than the aerial
84 components of forests (Soussana et al., 2010). But potential carbon
85 sequestration in soils under grasslands far from offsets the loss of above
86 ground vegetation in the majority of tropical areas, and therefore natural
87 vegetation should be preserved.

88 Brazil is the world's second largest beef producer – 9.3 Mt.yr⁻¹
89 (14.7% of the world's total), and the largest exporter in 2012-13 (FAO,

90 2014). Production is predominantly pasture-based in a grassland area of
91 approximately 170 Mha (IBGE, 2014), mostly in a humid or sub-humid
92 tropical climate.

93 But beef production can entail significant trade-offs, that must be
94 managed to minimize external costs. These include the controlled expansion
95 of agricultural area, associated deforestation, cost-effective greenhouse gas
96 mitigation, and land competition between food and biofuels.

97 Analysis of historical data (Martha et al., 2012) and scenario
98 studies conducted by the World Bank (Gouvello et al., 2011) suggest that
99 improving beef productivity has the highest potential to buffer the expansion
100 of other agricultural activities, avoiding further deforestation. Increasing
101 pasture productivity can also boost soil carbon sequestration, particularly
102 when carried out in currently degraded grasslands (Braz et al., 2013;
103 Ruviaro et al., 2014). In addition, increasing productivity through feed
104 supplementation may significantly reduce direct methane emissions (Berndt
105 and Tomkins, 2013; Ruviaro et al., 2014).

106 In this context and based on its previous National Plan on Climate
107 Change, at the Conference of the Parties 15 (COP 15), Brazil has proposed
108 Nationally Appropriate Mitigation Actions (NAMAs) as part of its
109 commitment to the United Nations Framework Convention on Climate
110 Change (<http://www.mmechanisms.org/e/namainfo/index.html>). Over the
111 period 2010-2020, the NAMAs establish targets for the reduction of
112 Amazon deforestation by 80% and by 40% in the *Cerrado* (Brazilian
113 Savannah), through the adoption of pasture recovery (15 Mha), and from
114 integrated crop-livestock-forestry systems (4 Mha). With these cattle-related
115 measures, Brazil expects to reduce net emissions by between 101 and 126
116 Mt CO₂-e, by 2020, which account for 61% - 73% of all mitigation in
117 agricultural practices by the NAMA route. The NAMA proposal is enacted
118 as part of the ambitious ABC (Agricultura de Baixo Carbono - Low Carbon

119 Agriculture) program, which offers low interest credit lines to farmers
120 adopting mitigation technologies (Mozzer, 2011).

121 This paper investigates the cost-effectiveness of key livestock
122 mitigation measures applicable in the *Cerrado* core (Central Brazilian
123 Savannah); a region that contains around 35% of the Brazilian herd
124 (Anualpec, 2010). The region is considered as central in Brazil's ascendance
125 in global production (The Economist, 2010; The New York Times, 2007)
126 and is still regarded as the most important region for expanding beef
127 production in Brazil (Ferraz and Felício, 2010). It is seen as a potential
128 model for transforming other savannahs (Morris et al., 2012).

129 The analytical focus is significant because there is currently little
130 research clearly demonstrating that mitigation through livestock
131 management can be delivered at relatively low cost. The paper offers the
132 first bottom-up cost-effectiveness analysis using an optimization model for
133 Brazilian beef production. The measures evaluated are pasture restoration,
134 feedlot finishing, supplement concentrates and protein and nitrification
135 inhibitors. The analysis uses the outputs of a multi-period linear
136 programming model (See Appendix S1) to develop a bottom-up or
137 engineering marginal abatement cost curve (MACC), to represent the
138 relative cost-effectiveness of measures and their cumulative abatement
139 potential above a baseline of business as usual (Moran et al., 2010). The
140 analysis examines the direct emissions reductions attributable to measures
141 enacted within the notional farm gate rather than wider life cycle impacts
142 (i.e., post farm gate), and accounts for both the private and social costs and
143 benefits (e.g. including avoided deforestation).

144 The paper offers new insights for regional policy and is structured
145 as follows. Section 2 outlines the modelling structure and relevant
146 optimization assumptions underlying the cost-effectiveness analysis. Section
147 3 describes the MACC calculation, while section 4 sets out results. Sections
148 5 and 6 offer a discussion and conclusions.

149

150 **2. Modelling methods for mitigation cost-effectiveness**

151

152 **2.1 Model Overview**

153

154 Abatement potential and cost-effectiveness of measures were derived
155 using a multi-period linear programming model (See Appendix S1 for
156 detailed mathematical description) that simulates a whole cycle (cow-calf,
157 stocking and finishing) beef production farm, accounting for: (i) herd
158 dynamics, (ii) financial resources, (iii) feed budgeting, (iv) land use: pasture
159 recovery dynamics and crops, and (v) soil carbon stock dynamics.

160 The model optimizes the use of the farm resources (capital, cattle,
161 land) while meeting demand projections and maximizing profit. In this
162 context the model is used to simulate beef production treating the *Cerrado*
163 region as a single farm. The farm activities (i-iii) are modelled using
164 monthly time steps, while (iv & v) are modelled using annual time steps.
165 The model represents animals in age cohorts k ; a steer of age cohort $k=1$, is
166 a calf aged 6 months, and 189 kg of live weight (LW). After 3 months in the
167 system, age cohort k is transferred to age cohort $k+1$, now with 222 kg of
168 LW. The final weight is 454 kg, corresponding to $k=9$ (33 months), when
169 the animal is sold and removed from the system.

170 The same cohorts apply to heifers, although these can also
171 accommodate breeding rates, where a heifer generates 1 calf per 18 month
172 cycle, comprising 9 months of pregnancy, 6 months of lactation (Millen et
173 al., 2011), plus 3 months of non-lactation and non-pregnancy. Half of the
174 calves born are allocated to steers and the other half are allocated to heifers,
175 both of age cohort $k=1$. After 4 cycles, the cows are removed from the
176 system and slaughtered, i.e., used to meet demand.

177 The model also simulates feedlot finishing, and thus allows the
178 reduction of the finishing time. It can remove a proportion of steers from

179 exclusive grazing, inserting the animals into feedlot systems; generally only
180 males are confined in Brazil (Millen et al., 2009; Costa Junior et al., 2013).
181 For all cattle categories, i.e., male, female, male in feedlot and breeding
182 females, the corresponding age cohort is associated with specific
183 parameters: weight, mortality rate, dry matter (DM) intake, selling and
184 purchase prices, emissions factors for CH₄ from enteric fermentation and
185 emissions factors for N₂O from excreta. The associated coefficient values
186 are detailed in Table S1 and Table S2.

187 The gross margin of the *Cerrado* single region farm is maximized
188 and calculated as the difference between the income and expenses. Income
189 derives exclusively from the sale of finished cattle, 454 kg of LW for steers
190 and 372 kg of LW for heifers. Farm expenses are composed of investment
191 and maintenance costs. Maintenance costs are (i) farm maintenance and (ii)
192 animal non-feed maintenance. Costs for (i) include working animals,
193 machinery and equipment, veterinary equipment, telephone device, fuel,
194 taxes and fees, totalling US\$ 25.00 ha⁻¹.yr⁻¹ (See Table S8 details). Costs for
195 (ii) were calculated for each age cohort and it is composed of cost of mineral
196 salt and expenses with health (vaccines), and animal identification (Table
197 S1).

198

199

200

201

202 **2.2 Land use dynamics**

203

204 The model simulates land use dynamics by allocating the total area
205 across pastures or crops; the latter being used for grain and silage production
206 to be used for the formulation of ration for feedlot and supplementation for
207 grazing cattle. The model allocates land into pasture, soybean and corn. In
208 the case of pasture, the model allocates land into different productivity

209 levels. Pasture degradation and restoration rates are key model processes
210 that have a bearing on overall system productivity and hence emissions
211 intensity of production.

212

213 **2.2.1 Grassland degradation**

214

215 Pasture degradation can be defined as the loss of vigour and
216 productivity of forage. To represent the degradation process, we define six
217 levels of Dry Matter Productivity (DMP): *A*, *B*, *C*, *D*, and *F* (Table 1), where
218 level *A* is the pasture of highest productivity, and level *F* is fully degraded.
219 If no action is taken to maintain or improve productivity of a fraction of the
220 area in a given level, it is relocated to a lower productivity level. So, after a
221 period of time (assumed as two years herein) category *A* degrades to
222 category *B*, *B* degrades to *C*, and so on, until pasture *F*, thus completing a 10
223 years full degradation (with no management interventions).

224 The DMP of the pastures levels were calculated exogenously using
225 a model that estimates seasonal pasture growth according to soil, species
226 and climate conditions (Tonato et al, 2010). Each pasture level of DMP is
227 associated with a carbon equilibrium value that is used to estimate changes
228 in soil organic carbon due to pasture management (see section 2.3 for
229 details).

230

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238 Table 1: Annual dry matter productivity and equilibrium C stock values in
 239 function of land use.

Land use	DM ¹ (t.ha ⁻¹ .yr ⁻¹)	Soil carbon stock equilibrium ² (t.ha ⁻¹)
Pasture A	19.6	84.3
Pasture B	17.6	82.7
Pasture C	12.6	62.3
Pasture D	8.7	45.2
Pasture E	5.8	32.4
Pasture F	3.9	26.1
Corn (Silage)	9.0	45.0
Corn (Grain)	3.8	40.0
Soybean	2.5	45.0

240

241 ¹ Estimated using the model published by Tonato et al. (2010)

242 ² According to Parton (1987)

243

244 2.2.2 Land use change and pasture restoration

245

246 To offset the degradation process the model can allow for grassland
 247 restoration through improved forage quality by direct restoration (by
 248 chemical and mechanical treatment) or indirect restoration (by rotating with
 249 crops). For example, in a given year a pasture *A* will degrade to *B*, the
 250 optimal solution might be letting half of pasture *A* to degrade, and half be
 251 maintained to level *A*. Furthermore, the model works simultaneously with a
 252 composition of pasture DMP levels; e.g., in a given year *t*, the composition
 253 can be 4% of *A*, 10 % of *B*, 85% of *C*, and 1% of soybean. Then, at year
 254 *t+1*, the composition can change by any combination among the pasture
 255 DMP levels and crops.

256 For each type of land use change or restoration, there is an
 257 associated cost (Table 2). Costs were calculated accounting for the amount
 258 of inputs and services (e.g., nitrogen, limestone, micronutrients, forage

259 seeds, internal transport) needed to maintain or increase the DMP level in
 260 the target pasture DMP level. For details of applied inputs, see Table S3-S7
 261 in Appendix S3.
 262
 263 Table 2: Costs of pasture restoration practices and crops planting. The table
 264 can be read as “the cost to restore one hectare of pasture “X” to an improved
 265 pasture “Y”, or in some cases, “the cost to move one hectare from land use
 266 “X” to land use “Y”, where “X” and “Y” are any element in the column
 267 “Pasture/Crop”. The case of $X=Y$ (table diagonal), represents the cost of
 268 maintaining a given pasture at the current DMP level (i.e., cost of avoiding
 269 degradation) or the cost of replant a crop in the same area.

Costs of pasture restoration practices/land use change ¹ (US\$2012.ha-1)									
Land use	Pasture A	Pasture B	Pasture C	Pasture D	Pasture D	Pasture F	Corn (Silage)	Corn (Grain)	Soybean
Pasture A	112.4	0.0	0.0	0.0	0.0	0.0	1352.6	600.0	345.4
Pasture B	149.9	72.7	0.0	0.0	0.0	0.0	1502.5	749.9	495.3
Pasture C	399.3	249.4	15.0	0.0	0.0	0.0	1751.9	999.3	744.7
Pasture D	630.0	480.0	230.7	9.4	0.0	0.0	1982.6	1229.9	975.3
Pasture D	724.6	574.6	325.2	94.6	5.6	0.0	2077.2	1324.5	1069.9
Pasture F	767.0	617.1	367.7	137.1	42.5	5.6	2119.6	1367.0	1112.4
Corn (Silage)	269.8	200.9	125.1	125.1	125.1	125.1	1630.7	1060.6	971.8
Corn (Grain)	269.8	200.9	125.1	125.1	125.1	125.1	1736.4	981.9	992.6
Soybean	269.8	200.9	125.1	125.1	125.1	125.1	1736.4	981.9	1017.7

270

271 ¹ See Appendix S2 for calculation details.

272

273 Land use change (including deforestation), degrading or restoring
 274 pasture will affect the soil carbon (C) stocks. These changes are calculated
 275 by estimating the annual C stock under pasture and crops for each land use.
 276 The total accumulated C under soils is given by the sum of the C stock of
 277 each pasture DMP levels, soybean and corn.

278

279 2.3 Carbon sequestration through pasture management

280

281 Depending on the DMP, the C flux may change significantly. The
282 model works with equilibrium values of the C stock for each type of pasture
283 and crops. The higher the pasture productivity, the higher the C equilibrium
284 value (Table 1). The equilibrium values were calculated exogenously, using
285 simulations from the CENTURY model (Parton et al., 1987) applied to
286 *Cerrado* biophysical characteristics and using the annual DMP calculated
287 for each pasture category.

288 The model accounts for the annual carbon stocks per each land use
289 in column 1, Table 1. The model transfers the accumulated carbon from year
290 $t-1$ to year t and calculates the variation of soil C in year t .

291 Letting $C_{t,lu}$ be the soil carbon stock (tonnes) under the land use lu ,
292 where $lu \in \{A, B, C, D, E, F, Soybean, Corn(silage), Corn(grain)\}$. Then
293 $C_{t,lu}$ can be expressed by:

294

$$295 \quad C_{t,lu} = \varphi(t,lu) + \Delta C_{t,lu} \quad (\text{Eq. 1})$$

296 And

$$297 \quad \Delta C_{t,lu} = f(\varepsilon_{lu}, C_{t-1,lu}) \quad (\text{Eq. 2})$$

298

299 Eq. (1) is composed of the carbon transference term, $\varphi(t,lu)$, and the C
300 sequestration term, $\Delta C_{t,lu}$. The term $\varphi(t,lu)$ accounts the transference of C
301 from other uses to land use lu in year t ; e.g., if lu is equal pasture B , and one
302 hectare of soybean is converted in year t into one hectare of pasture level B ,
303 the carbon previously stocked under soybean has to be transferred to pasture
304 B . Similarly, if some hectares are converted from pasture B to pasture A , or
305 degraded to C , then part of the C stock from B has to be proportionally
306 transferred from B to these other uses. The sequestration term, $\Delta C_{t,lu}$ is
307 written as a function of the difference between the previous C stock $C_{t-1,lu}$,
308 and the C stock equilibrium value, ε_{lu} . Hence the further the previous stock
309 is from the equilibrium value, the more C will be up taken. Conversely, if
310 due to the land use change, or degradation, the C stock becomes greater than

311 the equilibrium value, there will be negative C sequestration, i.e., a loss of C
312 stock. These modelling approaches follow the concepts suggested by
313 Eggleston et al. (2006) and Vuichard et al. (2007). The extended version of
314 Eq. (1) and (2) are presented in Appendix S1.

315

316

317 **2.4 Deforestation due to cattle ranching**

318

319 For pasture area we use the projections published by Gouvello et
320 al. (2011) combined with an endogenous deforestation term. Let LU_t be the
321 total area at year t ; a_t the exogenous projections; and D_t the endogenous
322 term that represents further area expansion. Then for every year:

323

$$324 \quad LU_t = a_t + D_t \quad (\text{Eq. 3})$$

325

326 The deforested area will cause a loss of carbon stocks in natural vegetation
327 and influence soil C; and directly influences the transference term in eq. (1),
328 i.e., loss of soil organic matter (SOM). Both vegetation carbon stocks and
329 SOM are accounted to represent the emissions associated with deforestation.

330 There is limited quantitative research accounting for the dynamics
331 of pasture productivity following deforestation. In accordance with the best
332 available information, the model allocates new converted areas into the
333 system in pasture category C (the highest without nitrogen fertilization), as
334 soil carbon also can increase or decrease values after deforestation (Maia et
335 al., 2009) and pasture productivity is relatively high after conversion due to
336 higher soil organic matter mineralization (Martha Jr, 2007). In this analysis,
337 we assumed the cost of opening new areas is zero because the cost of
338 conversion the *Cerrado* into pastures can be offset by timber sales and land
339 value appreciation (Bowman et. al, 2012).

340 Another assumption is that the model cannot discard land
341 endogenously, neither does it allow fallow in any year of the planning
342 period. This assumption is based on the fact that cattle ranchers are not
343 allowed to let their properties be unproductive; otherwise the land can be
344 confiscated by the government for agrarian reform (Federal Law 8.629 -
345 www.planalto.gov.br/ccivil_03/leis/18629.htm).

346

347 **2.5 Baseline construction**

348

349 Land use change scenarios need to be mapped onto a plausible
350 baseline for land use activity. The baseline scenario is based on national
351 forecasts of beef demand and grassland area for Brazil, from 2006 to 2030
352 (Gouvello et al., 2011). The assumption is that the attributable *Cerrado*
353 pasture area and beef demand share are a fixed proportion of the national
354 projections. In 2006, the *Cerrado* pasture area represented 34% of the
355 national total (IBGE, 2014). The model then assumes that *Cerrado* pasture
356 area corresponds to 34% of Brazil's pasture area, and this proportion is
357 constant during the studied period (2006-2030). Similarly, as there is no data
358 for regional demand, we assumed demand to be proportional to area, i.e.,
359 demand for *Cerrado* is also equivalent to 34% of national demand, this
360 percentage is very close to the 35% figure estimated by Anualpec (2010).

361 In the model, increased productivity occurs by means of
362 investments in technologies, e.g., pasture restoration, supplementation and
363 feedlot animals. The baseline scenario has limited adoption of these
364 measures, implying constant productivity. We assumed that pasture
365 restoration is allowed in the baseline only to avoid degradation, but it is
366 constrained to maintain productivity at 2006 levels ($10 \text{ t-DM}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$, as
367 calculated in Appendix S2). Combining this constraint with projected
368 increased demand pushes the model to open new areas if it is necessary to
369 meet the growing demand for beef.

370 The current adoption rate of feedlot finishing in Brazil is around
371 10% of the total herd (Anualpec, 2010). We assumed this proportion to be
372 constant in the baseline, a rate that is in counterpoint to a higher level of
373 penetration of this measure in a mitigation counterfactual.

374

375 **2.6 GHG emissions sources**

376

377 The model calculates GHG emissions using emissions factors for
378 activities within the farm gate. GHG emissions associated with the farm
379 activities are: (a) CH₄ from cattle enteric fermentation (CH₄ from excreta is
380 not accounted); (b) N₂O from cattle excreta; (c) N₂O direct emissions from
381 N fertilization; (d) CO₂ from deforestation; and (e) CO₂ from pasture
382 degradation and land use change from pasture to crops. Items (a) and (b)
383 depend on herd composition: each age cohort of males and females (heifer
384 or cow) has an associated emission factor of CH₄ and N₂O calculated using
385 Tier 2 methodology (Eggleston et al., 2006), see Table S1 and Table S2.
386 Due to the lack of studies in Brazilian conditions, for (c), we used the Tier 1
387 IPCC default factor of 1% (Eggleston et al., 2006). The emissions from (d)
388 are calculated using coefficient of loss of natural vegetation per deforested
389 area. The average carbon loss of natural vegetation due to deforestation was
390 estimated as 34.6 tonnes of C per hectare, in accordance to Eggleston et al.
391 (2006) and Bustamante et al. (2012). For (e), the emissions are calculated
392 according to Eq. (1) and (2).

393

394 **2.7 Mitigation Measures**

395

396 The selection of GHG mitigation measures was based on literature
397 review and expert opinion regarding the relevance and applicability of the
398 technologies to Brazilian livestock production and conditions. The measures
399 evaluated are: concentrate supplementation, protein supplementation,

400 pasture restoration, nitrification inhibitors and feedlot finishing. Although
401 the latter is already in the baseline, we investigated a higher adoption rate of
402 this technology.

403 Modelling assumptions for these measures related to the effects the
404 measures have upon the gross margin and emissions are detailed in Table 3.

405 Table 3: Selected livestock mitigation measures

Mitigation measure	Description	Cost ¹	Unit	Reduces emissions by:	Adoption rate target
Feedlot finishing	When cattle weight is around 80% of the slaughter weight it is removed from pasture and grass to feedlot on a diet with ration of balanced protein and energy content	9.12	\$.head ⁻¹ .mth ⁻¹	Shorter animal life cycle by increasing weight gain	15% of the total finished animals.
Nitrification inhibitors	Application of Agrotain Plus® together with urea used as fertilizer; 3 g per Kg of applied nitrogen ²	61.44	\$.t ⁻¹	Reduced conversion of nitrogen to the GHG nitrous oxide (nitrification)	Optimized
Pasture restoration	Improving pasture forage productivity by soil chemical and mechanical treatment. As described in Section 2.1	Table 2	\$.ha ⁻¹	Avoiding the need for additional pasture land and increasing organic carbon sequestration	Optimized
Supplementation concentrate	Feeding cattle via grazing and a ration with a high energy content. Grazing steers with 421 kg of LW can be selected for concentrate supplementation. The supplementation takes 2 months and the final weight is 490 kg	3.07	\$.head ⁻¹ .mth ⁻¹	Shorter animal life cycle by increasing weight gain	Optimized
Supplementation protein	Feeding cattle via grazing and a ration with a high protein content. Calves (189 kg) can be selected (only in March) to be supplemented with protein. The steers are finished after 15 months, with 481 kg	1.15	\$.head ⁻¹ .mth ⁻¹	Shorter animal life cycle by increasing weight gain	Optimized

406

407 ¹ In the case of supplementations the values refer to non-feed costs, for feed costs see ration formulation (Table 4)

408 ² According to manufacturer's recommendation (<http://www.agrotain.com/us/home>).

409

410 **2.7.1 Concentrate and protein supplementation**

411

412 Both measures involve supplementing the feed of grazing steers;
413 e.g., feed is composed of forage and supplements. It is expected that these
414 measures reduce emissions since animals gain weight faster and take less
415 time to be finished.

416

417 Table 4: Rations (supplements) formulation and costs.

Crop	Ration Formulation (%) ¹			Cost ² (US\$.kg ⁻¹)
	Feedlot	Concentrate	Protein	
Corn (grain)	83	80	15	PBF
Corn (Silage)	11	0	0	PBF
Soybean	5	17	39	PBF
Urea	0	2	12	1.19
Mineral Salt	1	1	19	0.84
NaCl	0	0	15	1.19

418

419 ¹ Rations were formulated by using the software Invernada (minimum cost
420 ration formulator) (Barioni, 2011)

421 ² PBF = Produced by the farm, i.e., corn and soybean are not purchased but
422 produced endogenously in the model.

423

424 Biological coefficients, e.g., mortality rate, weight, DM intake, and
425 emissions factor for steers fed with supplementations can be found in Table
426 S2.

427

428 **2.7.2 Pasture restoration**

429

430 This measure works in the model by avoiding deforestation and
431 because restoration boosts carbon soil uptake. Details of the modelling and

432 costs are explained in section 2.2.2. In contrast to the baseline scenario, to
433 evaluate this measure, the fixed DMP baseline constraint was removed.

434

435 **2.7.3 Nitrification Inhibitors**

436

437 The measure works by avoiding a proportion of the N in fertilizer
438 or manure being converted into N₂O, i.e. nitrification and denitrification
439 process (Abbasi and Adams, 2000). To date there have been no studies
440 detailing the reduction in N₂O emissions for Brazilian pastures when
441 nitrogen inhibitors are applied. A 50% reduction of direct N₂O emissions is
442 assumed in this paper - as found by Giltrap et al. (2011) for a New Zealand
443 study. We assumed that this measure is applicable only over the N used for
444 pasture and crops fertilization. The reason is that most of the Brazilian herd
445 is based on a grazing system where it is unfeasible to apply inhibitors to
446 animal excreta.

447

448 **2.7.4 Feedlot finishing**

449

450 Like supplementation, this measure works by reducing the cattle
451 finishing time since feedlot animals are fed only by ration (with the
452 formulation described in Table 4). Only steers can be selected to model in
453 the feedlot system. The adoption rate was arbitrarily assumed to be 15% of
454 the total finished herd, since in the baseline the adoption rate is 10% of the
455 total finished herd, the measure can be stated as: increasing by 50% over the
456 baseline adoption rate.

457

458 **3.1 Marginal abatement cost curve**

459

460 A MACC can be used to represent the relative cost-effectiveness of
461 different abatement options and the total amount of GHG that can be abated

462 by applying mitigation measures over and above a baseline scenario. The
463 aim is to identify the most economically efficient manner to achieve
464 emissions reduction targets, where the cheapest units of greenhouse gas
465 should be abated first (Moran et al., 2010).

466 MACC analysis can be derived by means of a top-down analysis –
467 which usually makes use of a general equilibrium model and emissions are
468 calculated endogenously, or by a bottom-up or engineering analysis
469 (MacLeod et al., 2010). This paper takes a bottom-up approach, where the
470 individual abatement potential of measures and their costs are individually
471 modelled.

472 The MACC can be presented in form of a histogram, where the C
473 abatement potential lies on the x-axis, and the cost per tonnes of abatement
474 in the y-axis. The abatement potential of a measure m (AP_m) is calculated as
475 the annual average of the difference between the business-as-usual
476 (baseline) total GHG emissions (E_{BAU}) and the total emissions under the
477 mitigation measure scenario (E_m) during the production period T :

478

$$479 \quad AP_m = \frac{E_{BAU} - E_m}{T} \quad (\text{Eq. 4})$$

480

481 The cost-effectiveness of measure m (CE_m), therefore, is calculated by:

$$482 \quad CE_m = \frac{GM_{BAU} - GM_m}{AP_m} \quad (\text{Eq. 5})$$

483

484 Where GM_{BAU} and GM_m are, respectively, the gross margin in the baseline
485 scenario and the gross margin in the scenario with the measure m
486 implemented.

487

488 As observed in Eq.4 and Eq.5, AP_m and CE_m are average values across the
489 planning period.

490 **4. Results**

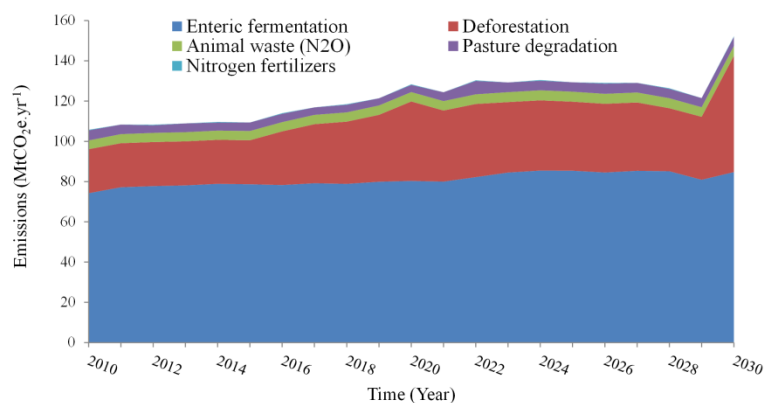
491

492 **4.1 Baseline Emissions**

493

494 In the baseline scenario, beef production in the *Cerrado* accounts
495 for an average of 121.5 Mt CO₂e.yr⁻¹, from 2010 to 2030. This value
496 includes enteric fermentation, animal waste (emissions from excreta), soil
497 fertilization emissions, pasture (due to the loss in C stocks), and
498 deforestation driven by cattle production (Fig. 1). The accumulated
499 emissions from 2010 to 2020 account for about 1,249 Mt CO₂e or 2,551 Mt
500 CO₂e from 2010 to 2030.

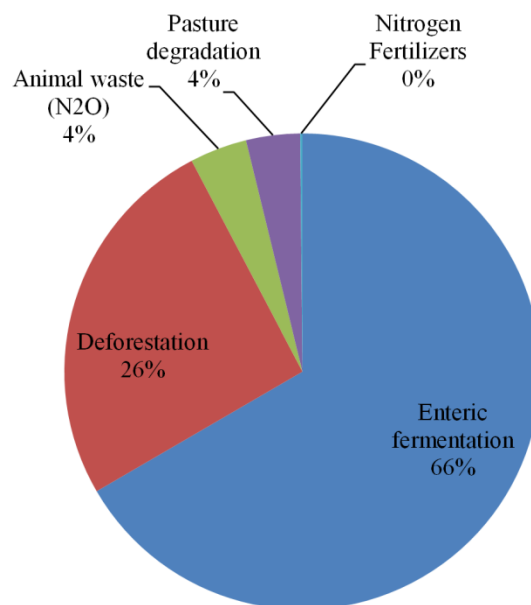
501 In relative terms, enteric fermentation makes the biggest
502 contribution to the total: 66% of emissions, followed by deforestation, with
503 26%. The results also show that pasture degradation is a considerable source
504 of emissions, accounting for an average of 8.35 Mt CO₂e.yr⁻¹ (an average of
505 0.06 t CO₂e.ha⁻¹.yr⁻¹), the equivalent to 4% of emissions or the same
506 proportion as animal waste (Fig. 2).



507

508 **Figure 1:** Baseline emissions of beef production in the Brazilian *Cerrado* for
509 the 2010-2030 period according to: nitrogen fertilizer (applied to pastures
510 restoration and crops plantation), animal waste (cattle direct N₂O emissions

511 through excreta), pasture degradation (loss of soil organic carbon) and
512 deforestation (loss of above ground organic carbon).
513
514 Gouvello et al. (2011) suggests that total national GHG emissions from
515 energy, transport, waste, livestock and agriculture, will be around 1.70 Gt
516 CO₂e by 2030. The results presented here suggest that beef production in
517 the *Cerrado* will be responsible for about 152 Mt CO₂e in 2030,
518 corresponding to 9% of total national GHG emissions.
519



520
521
522 Figure 2: Share of the main GHG emissions sources from beef production in
523 the Brazilian *Cerrado*. The values relates to the proportion of each source in
524 relation to the accumulated emissions for the period 2010-2030.

525
526 In the baseline scenario, without increasing productivity, an
527 average deforestation rate of $246.1 \cdot 10^3 \text{ ha}\cdot\text{yr}^{-1}$ would be required to meet the
528 beef demand projections.

529 Emissions attributed to the use of fertilizers were not significant,
530 accounting for an average of $0.2 \text{ Mt CO}_2\text{e}\cdot\text{yr}^{-1}$. This was expected, since

531 small amounts of N are used to fertilize *Cerrado* pasture soils (Martha Jr et
532 al., 2007; Cederberg et al, 2009).

533

534 **4.2 Cost-effectiveness analysis**

535

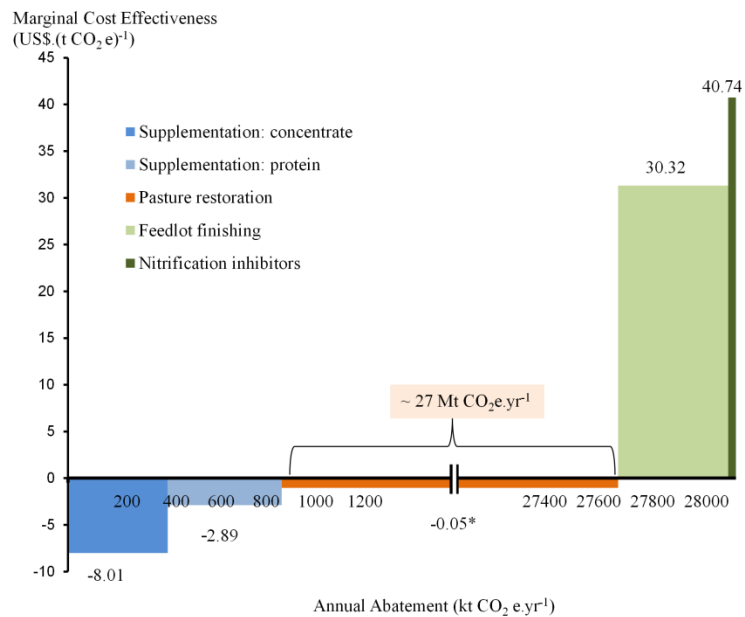
536 For policy purposes it is important to detail the relative cost of
537 emissions mitigation measures. Three of the five mitigation measures
538 simulated, - concentrate supplementation, protein supplementation, and
539 pasture restoration - have negative cost-effectiveness: US\$-8.01. t CO₂e⁻¹,
540 US\$-2.88. t CO₂e⁻¹ and US\$-0.05. t CO₂e⁻¹, respectively (Figure 3).

541 Adopting these measures implies cost savings while reducing emissions.

542 These measures work by balancing the loss of DM production during the
543 dry months. The *Cerrado* biome is predominantly seasonal tropical,
544 meaning dry winters and rainy summers, with lower pasture productivity
545 during the dry months. If cattle are supplemented with concentrates or
546 protein they can be finished earlier, thereby reducing emissions.

547 Due to the large applicable area (approximately 60 Mha), and given
548 the current low productivity of 10 t DM.ha⁻¹.yr⁻¹, pasture restoration
549 provides the biggest opportunity for reducing emissions in the region.

550



551
552

553 Figure 3: Marginal abatement cost schedule of key mitigation measures
554 applicable to beef production in the *Cerrado*. The abatement potential (x-
555 axis) and cost effectiveness (y-axis) of each measure was calculated as the
556 average values obtained by adopting the measure over the 2006-2030
557 period.

558

559 The figures are average values for the period of 2006-2030.

560 * Not in scale

561

562 The abatement potential (AP) for pasture restoration is 26.9 Mt
563 CO₂e.yr⁻¹, comprising of two components: C sequestration and avoided
564 deforestation, the latter accounting for 96% of this AP. Despite improved
565 pasture productivity, less area is used to meet the same demand relative to
566 the baseline, what means forage availability optimally matches that required
567 for demand. In a scenario of increased forage productivity and higher beef
568 demand, methane emissions would rise as result of increased animal
569 numbers. Pasture restoration would improve the *Cerrado* average

570 productivity from 10 to 11.2 t DM.ha⁻¹.yr⁻¹, an increase of 12% relative to
 571 the baseline. This increase would lead to an average C sequestration rate of
 572 0.32 t CO₂e.ha⁻¹.yr⁻¹. This is a low C uptake potential when compared to
 573 values found by Maia et al. (2009), which showed that C sequestration rates
 574 of 2.24 t CO₂e.ha⁻¹.yr⁻¹ can be achieved in well-managed pastures in
 575 *Cerrado*. The carbon sequestration rate however, reflect the 2006-2030
 576 period, after which, and in the long term, as pastures are intensified it will
 577 eventually reach equilibrium and therefore no more carbon is likely to be
 578 sequestered.

579 The AP of feedlot finishing is 470 kt CO₂e.yr⁻¹, but the measure
 580 cost-effectiveness US\$ 13.32 t CO₂e⁻¹ is high relative to supplementation.

581 Nitrification inhibitors are the least cost-effective measure
 582 considered. But this analysis only considered the application to N used for
 583 pasture and crops fertilization and excluded the application to animal
 584 excreta.

585 The results indicate that restoring degraded lands is the biggest
 586 opportunity for reducing emissions in the *Cerrado*. The AP of this measure
 587 is about 20 times greater than all the other measures combined.

588 An important assumption underpinning the MACC relates to the
 589 assumed measure adoption rates. With exception of feedlot finishing, the
 590 adoption rates are optimized, meaning the rates that maximizes the gross
 591 margin in the model.

592

593 Table 5: Mitigation measures adoption rate.

Mitigation Measure	Adoption rate	Unit
Supplementation: concentrate	12	% ¹
Supplementation: protein	2.2	%
Pasture restoration	314.7	10 ³ ha.yr ⁻¹
Feedlot finishing	15	%
Nitrification inhibitors	12.78	g.ha ⁻¹ .yr ⁻¹

594

595 ¹ Adoption rates for feedlot, protein and concentrate supplementation are
596 calculated as the percentage of the total finished animals. The adoption rate
597 of pasture restoration is the annual average area of restored pasture.

598

599 **5. Discussion**

600

601 To meet increasing domestic and export demand, the government
602 of Brazil recognizes the need to foster sustainable agricultural
603 intensification, which implies increased resource productivity while
604 minimizing significant domestic and global external costs implicit in GHG
605 emissions and deforestation. The results presented here suggest that a
606 significant contribution to this objective can be made by targeting specific
607 measures to improve yield. Specifically, pasture restoration, supplements
608 and feedlot measures could reduce sector emissions by 24.1% by 2030.
609 Moreover, by adopting only negative-cost measures (Fig. 3), it is possible to
610 abate about 23.7% of baseline livestock emissions in the *Cerrado*, up to
611 2030. According to our results the restoration of degraded pastures offers
612 the greatest abatement potential, involving the restoration of an average of
613 $314.7 \cdot 10^3 \text{ ha}\cdot\text{yr}^{-1}$ in *Cerrado* grasslands.

614 Currently, it has been estimated that 50 % to 80 % of pastures in
615 the Amazon and *Cerrado* are degraded (Macedo et al., 2014; Peron &
616 Evangelista, 2004). Achieving a higher rate is likely to entail some initial
617 investment costs to promote modified production practices and this is the
618 purpose of the government's ABC program. ABC is an ambitious plan
619 created to stimulate farmers and ranchers to adopt mitigation measures
620 including restoration of degraded pastures, helping the country to meet the
621 reduction targets presented at COP 15. ABC is the biggest sustainable
622 agriculture fund running in Brazil, with a key objective of disbursing
623 subsidized credit to the agricultural sector. The plan currently targets the
624 recovery of 15 Mha in 10 years, which will lead to reductions up to 104 Mt

625 CO₂e, roughly 64% of the program total mitigation potential. But it does
626 not include other relevant measures such as feed supplementation measures,
627 which would normally be considered as privately profitable anyway.

628 The outcome of the ABC plan remains to be evaluated, but initial
629 indications suggest that uptake of credit has been slower than anticipated
630 (Claudio, 2012). Recent evidence from the Amazon Environmental
631 Research Institute suggests that several institutional barriers have retarded
632 the program, including a lack of publicity and information about the aims
633 and the benefits of the program, difficulties in complying with program
634 requirements, a lack of technical assistance, and producer scepticism about
635 the private economic benefits of measures that are predominantly designed
636 to address global external costs (Stabile et al., 2012).

637 Producers also perceive transaction costs in program compliance
638 and a lack of basic infrastructure (Rada, 2013) that is needed to support
639 increased productivity. In short, the ABC plan is confronting similar
640 behavioural barriers in relation to non-adoption, identified in other
641 mitigation studies, e.g. Moran et al. (2013), which need to be addressed
642 before wider measure adoption can be expected.

643

644 **6. Conclusion**

645

646 This paper highlights how resource efficiency measures can be
647 enacted (notionally within farm gate) in the *Cerrado* biome to help reconcile
648 competing objectives of private yield improvements and the reduction of
649 external costs. The analysis responds to the need to demonstrate the
650 possibilities for sustainable intensification, allowing Brazil to meet
651 economic growth ambitions for the sector.

652 The key finding from the use of the economic optimization model
653 is the representation of the cost-effectiveness of key mitigation measures.
654 Specifically, that pasture restoration is the most promising mitigation

655 measure in terms of abatement potential volume and that it offers a cost
656 saving for the livestock sector. By adopting these measures - pasture
657 restoration, concentrate and protein supplementations - the *Cerrado* could
658 reduce 23.7% of its emissions by 2030, while the total abatement potential
659 of adopting all measures is 24.1%.

660 The analysis presented here has a number of caveats that
661 potentially warrant further research. These include a more detailed
662 representation of the biophysical heterogeneity of the *Cerrado* biome, more
663 detailed treatment of the deforestation (and hence land sparing) processes
664 and relaxation of the assumed equilibrium supply and demand conditions in
665 the optimization model.

666 Nevertheless by highlighting cost-effective policy options, this
667 paper contributes to our understanding of sustainable intensification
668 processes as relevant to Brazilian livestock production.

669

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671

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682

683 **References**

684

685 Abbasi, M.K., Adams, W.A., 2000. Estimation of simultaneous nitrification
686 and denitrification in grassland soil associated with urea-N using 15 N
687 and nitrification inhibitor. *Biol. Fertil. Soils* 31, 38–44.
688 doi:10.1007/s003740050621
689
690 Anualpec, 2010. Anualpec : anuário da pecuária brasileira. São Paulo, São
691 Paulo.
692
693 Barioni, L.G., 2011. Embrapa Invernada [computer software]. Ver.
694 1.2.27.45. URL <http://www.invernada.cnptia.embrapa.br> (accessed
695 12.03.15)
696
697 Berndt, A., Tomkins, N.W., 2013. Measurement and mitigation of methane
698 emissions from beef cattle in tropical grazing systems: a perspective
699 from Australia and Brazil. *Anim. An Int. J. Anim. Biosci.* 7 Suppl 2,
700 363–372. doi:10.1017/S1751731113000670
701
702 Bowman, M.S., Soares-Filho, B.S., Merry, F.D., Nepstad, D.C., Rodrigues,
703 H., Almeida, O.T., 2012. Persistence of cattle ranching in the Brazilian
704 Amazon: A spatial analysis of the rationale for beef production. *Land*
705 *use policy* 29, 558–568. doi:10.1016/j.landusepol.2011.09.009
706
707 Braz, S.P., URQUIAGA, S., SANTOS, C.A. dos., PINHEIRO, E.F.M.,
708 JANTALIA, C.P., BODDEY, R.M., 2013. Soil Carbon Stocks under
709 Productive and Degraded Brachiaria Pastures in the Brazilian Cerrado.
710 *Soil Sci. Soc. Am. J.* VO - 77 914.
711
712 Bustamante, M.M.C., Nobre, C. a., Smeraldi, R., Aguiar, A.P.D., Barioni,
713 L.G., Ferreira, L.G., Longo, K., May, P., Pinto, A.S., Ometto, J.P.H.B.,
714 2012. Estimating greenhouse gas emissions from cattle raising in
715 Brazil. *Clim. Change* 115, 559–577. doi:10.1007/s10584-012-0443-3
716
717
718 Cederberg, C., Meyer, D., & Flysjö, A., 2009. Life cycle inventory of
719 greenhouse gas emissions and use of land and energy in Brazilian beef
720 production. SIK-Institutet för livsmedel och bioteknik.
721 URL <http://www.sik.se/archive/pdf-filer-katalog/SR792.pdf> (accessed
722 23.03.2015)
723
724 Claudio, A., 2012. Brazil's fund for low-carbon agriculture lies fallow.
725 *Nature*. doi:10.1038/nature.2012.11111
726
727 Costa Junior, C., Goulart, R.S., Albertini, T.Z., Feigl, B.J., Cerri, C.E.P.,
728 Vasconcelos, J.T., Bernoux, M., Lanna, D.P.D., Cerri, C.C., 2013.
729 Brazilian beef cattle feedlot manure management: A country survey. *J.*
730 *Anim. Sci.* 91, 1811–1818.
731
732 Eggleston, S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., 2006. IPCC
733 guidelines for national greenhouse gas inventories. Hayama, Japan.
734
735 FAO, 2014. The Statistics Division of the FAO (Food and Agriculture
736 Organization of the United Nations) [WWW Document]. URL
737 <http://faostat.fao.org/> (accessed 3.17.14).
738
739 Ferraz, J.B.S., Felício, P.E. De, 2010. Production systems--an example from
740 Brazil. *Meat Sci.* 84, 238–43. doi:10.1016/j.meatsci.2009.06.006
741

- 742 Follett, R.F., Reed, D.A., 2010. Soil Carbon Sequestration in Grazing Lands:
743 Societal Benefits and Policy Implications. *Rangel. Ecol. Manag.* 63,
744 4–15.
745
- 746 Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J.,
747 Falcucci, A. & Tempio, G., 2013. Tackling climate change through
748 livestock – A global assessment of emissions and mitigation
749 opportunities. Rome.
750
- 751 Giltrap, D.L., Saggar, S., Singh, J., Harvey, M., McMillan, A., Laubach, J.,
752 2011. Field-scale verification of nitrous oxide emission reduction with
753 DCD in dairy-grazed pasture using measurements and modelling. *Soil*
754 *Res.* 49, 696. doi:10.1071/SR11090
755
- 756 Gouvello, C. de, Filho, B.S.S., Hissa, L., Nassar, A., Harfuch, L., Moreira,
757 M.M.R., Luciane Chiodi, Antoniazzi, L.B., Antoniazzi, B.B., Barioni,
758 L.G., Junior, G.M., Sainz, R.D., Alves, B.J.R., Lima, M.A. de,
759 Martins, O., Branco, M.C., Toledo, R., Verde, M.R.L., Marques, F.,
760 Ferreira, R., Goulart, L., Mendes, T., Moreira, A., Farinelli, B., Chang,
761 J.M., Pinto, R., Hato, J., Pacca, S., Freitas, S.R., Longo, K.M.,
762 Siqueira, R.A. de, 2011. Brazil Low Carbon Case study: Technical
763 Synthesis Report. The World Bank Group, Washington,DC.
764
- 765 IBGE, 2014. Agricultural Census 2006 [WWW Document]. Brazilian Inst.
766 Geogr. Stat. URL <http://www.sidra.ibge.gov.br/bda/acervo/acervo2.asp>
767 (accessed 3.17.14).
768
- 769 Macedo, M.C.M., Zimmer, A.H., Kichel, A.N., de Almeida, R.G., de Araújo,
770 A.R., 2014. Degradação de pastagens, alternativas de recuperação e
771 renovação, e formas de mitigação, in: *Embrapa Gado de Corte-Artigo*
772 *Em Anais de Congresso (ALICE)*. Ribeirão Preto, SP, pp. 158–181.
773
774
- 775 MacLeod, M., Moran, D., Eory, V., Rees, R.M., Barnes, A., Topp, C.F.E.,
776 Ball, B., Hoad, S., Wall, E., McVittie, A., Pajot, G., Matthews, R.,
777 Smith, P., Moxey, A., 2010. Developing greenhouse gas marginal
778 abatement cost curves for agricultural emissions from crops and soils
779 in the UK. *Agric. Syst.* 103, 198–209. doi:10.1016/j.agsy.2010.01.002
780
- 781 Maia, S.M.F., Ogle, S.M., Cerri, C.E.P., Cerri, C.C., 2009. Effect of
782 grassland management on soil carbon sequestration in Rondônia and
783 Mato Grosso states, Brazil. *Geoderma* 149, 84–91.
784 doi:10.1016/j.geoderma.2008.11.023
785
786
- 787 Martha Jr, G.B., 2007. Cerrado: uso eficiente de corretivos e fertilizantes em
788 pastagens, 1st ed. Planaltina - DF. URL
789 [http://www.sciencedirect.com/science/article/pii/S0308521](http://www.sciencedirect.com/science/article/pii/S0308521X12000340)
790 [X12000340](http://www.sciencedirect.com/science/article/pii/S0308521X12000340) (assessed 3.26.2015)
791
- 792 Martha, G.B., Alves, E., Contini, E., 2012. Land-saving approaches and beef
793 production growth in Brazil. *Agric. Syst.* 110, 173–177.
794 doi:10.1016/j.agsy.2012.03.001
795
796
- 797 Millen, D.D., Pacheco, R.D.L., Arrigoni, M.D.B., Galyean, M.L.,
798 Vasconcelos, J.T., 2009. A snapshot of management practices and

799 nutritional recommendations used by feedlot nutritionists in Brazil. *J.*
800 *Anim. Sci.* 87, 3427–39. doi:10.2527/jas.2009-1880
801
802 Millen, D.D., Pacheco, R.D.L., Meyer, P.M., Rodrigues, P.H.M., De Beni
803 Arrigoni, M., 2011. Current outlook and future perspectives of beef
804 production in Brazil. *Anim. Front.* 1, 46–52. doi:10.2527/af.2011-
805 0017
806
807
808 Moran, D., MacLeod, M., Wall, E., Eory, V., McVittie, A., Barnes, A., Rees,
809 R.M., Topp, C.F.E., Pajot, G., Matthews, R., Smith, P., Moxey, A.,
810 2010. Developing carbon budgets for UK agriculture, land-use, land-
811 use change and forestry out to 2022. *Clim. Change* 105, 529–553.
812 doi:10.1007/s10584-010-9898-2
813
814 Moran, D., Lucas, A., Barnes, A., 2013. Mitigation win–win. *Nat. Clim.*
815 *Chang.* 3, 611–613. doi:10.1038/nclimate1922
816
817 Morris, M., Binswanger, H., Byerlee, D., Staatz, J., 2012. A Breadbasket
818 for Africa: Farming in the Guinea Savannah Zone. *Solutions* 3, 44–49.
819
820 Mozzer, G.B., 2011. Agriculture and cattle raising in the context of a low
821 carbon economy, in: Seroa da Motta, R. (ed.), *climate change in brazil*
822 *Economic, Social and Regulatory Aspects.* IPEA, Brasília, DF, p. 358.
823
824 Neely, C., Bunning, S., Wilkes, A., 2009. Review of evidence on drylands
825 pastoral systems and climate change / Implications and opportunities
826 for mitigation and adaptation. Rome, FAO. URL
827 ftp://ftp.fao.org/docrep/fao/012/i1135e/i1135e00.pdf (Assessed
828 03.26.15)
829
830 Opio, C., Gerber, P., Mottet, A., Falcucci, A., Tempio, G., MacLeod, M.,
831 Vellinga, T., Henderson, B., & Steinfeld, H., 2013. Greenhouse gas
832 emissions from ruminant supply chains – A global life cycle
833 assessment. Rome.
834
835 Parton, W.J., Schimel, D.S., Cole, C. V, Ojima, D.S., 1987. Analysis of
836 Factors Controlling Soil Organic Matter Levels in Great Plains
837 Grasslands1. *Soil Sci. Soc. Am. J.* 51, 1173.
838 doi:10.2136/sssaj1987.03615995005100050015x
839
840 Peron, A.J., Evangelista, A.R., 2004. Degradação de pastagens em regiões
841 de cerrado. *Ciência e Agrotecnologia* 28, 655–
842 661.
843
844
845 Rada, N., 2013. Assessing Brazil’s Cerrado agricultural miracle. *Food*
846 *Policy* 38, 146–155. doi:10.1016/j.foodpol.2012.11.002
847
848 Ruviaro, C.F., de Léis, C.M., Lampert, V. do N., Barcellos, J.O.J., Dewes,
849 H., 2014. Carbon footprint in different beef production systems on a
850 southern Brazilian farm: a case study. *J. Clean. Prod.*
851 doi:10.1016/j.jclepro.2014.01.037
852
853 Soussana, J.F., Tallec, T., Blanfort, V., 2010. Mitigating the greenhouse gas
854 balance of ruminant production systems through carbon sequestration in
855 grasslands. *Animal* 4, 334–50. doi:10.1017/S1751731109990784

856
857 Soussana, J.F., Barioni, L.G., Ari, T.B., Conant, R., Gerber, P., Havlik, P.,
858 Ickowicz, A., Howden, M., 2013. Managing grassland systems in a
859 changing climate: the search for practical solutions, in: Revitalising
860 Grasslands to Sustain Our Communities: Proceedings. Sydney, p. 22.
861
862 Stabile, M.C.C., Azevedo, A., Nepstad, D., 2012. Brazil's "low-carbon
863 agriculture" program: barriers to implementation. Brasília. URL
864 [http://www.gcftaskforce.org/documents/brazil's_low-](http://www.gcftaskforce.org/documents/brazil's_low-carbon_agriculture_program.pdf)
865 [carbon_agriculture_program.pdf](http://www.gcftaskforce.org/documents/brazil's_low-carbon_agriculture_program.pdf) (Assessed 03.26.2015)
866
867 The Economist, 2010. The miracle of the cerrado; Brazilian agriculture.
868 Econ. VO - 396 59. URL
869 <http://www.economist.com/node/16886442> (Assessed
870 03.26.2015)
871
872 The New York Times, 2007. Scientists Are Making Brazil's Savannah
873 Bloom. New York Times VO - 157 3. URL
874 <http://www.nytimes.com/2007/10/02/science/02tropic.htm>
875 [l?pagewanted=all&_r=0](http://www.nytimes.com/2007/10/02/science/02tropic.htm) (Assessed 03.26.2015)
876
877 Thornton, P.K., Herrero, M., 2010. Potential for reduced methane and
878 carbon dioxide emissions from livestock and pasture management in
879 the tropics. Proc. Natl. Acad. Sci. 107 , 19667–19672.
880 doi:10.1073/pnas.0912890107
881
882 Tonato, F., Barioni, L.G., Guilherme, C., Pedreira, S., 2010.
883 Desenvolvimento de modelos preditores de acúmulo de forragem em
884 pastagens tropicais. Pesq. agropec. bras. 45, 522–529.
885
886 Vuichard, N., Ciais, P., Viovy, N., Calanca, P., Soussana, J.-F., 2007.
887 Estimating the greenhouse gas fluxes of European grasslands with a
888 process-based model: 2. Simulations at the continental level. Global
889 Biogeochem. Cycles 21, n/a–n/a. doi:10.1029/2005GB002612
890

891 **Appendix. Supplementary material**

892 Appendix S1: Mathematical description

893 Appendix S2: Calculation of restoration costs and model calibration

894 Appendix S3: Supplementary tables S1-S8

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902 **Mathematical description**

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905 List of indexes

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Symbol	Description	Range/value
i,j	Land use	{A, B, C, D, E, F, Corn(silage), Corn(grain), Soybeans}
p,q	Pasture level	{A, B, C, D, E, F}
c	Crops	{Corn(silage), Corn(grain), Soybeans}
kc	Cow breeding stage	{1, 2, ..., 12}
kh	Heifer age cohort	{1, 2, ..., 9}
ks	Steer age cohort	{1, 2, ..., 9}
kp	Age cohort of protein supplemented steers	{1, 2, ..., 6}
m	Production month	{1,2,...,M}
$CM_{(m)}$	Calendar month equivalent to production month m	{Jan, Feb, ..., Dec}
t	Year	{1, 2, ..., T}
$t_{(m)}$	Corresponding year to the production month m	{1, 2, ..., T}

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909 List of decision variables

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Symbol	Description	Unit
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$CASH_m$	Cash in month m	M R\$
CIN_m	Cash incomes in month m	M R\$
$CNIH_m$	Costs of nitrification inhibitors in month m	M R\$
COT_m	Cash outcomes in month m	M R\$
CSC_m	Concentrate supplementation costs in month m	M R\$
CSP_m	Protein supplementation costs in month m	M R\$
EDA_t	Endogenous deforestation in year t	M ha
FSC_m	Number of finished steers under concentrate supplementation at month m	M head
FSF_m	Number of steers finished under feedlot system in month m	M head
IC_m	Number of cows inserted in the system in month m	M head
$IH_{m,kh}$	Number of heifers of age cohort kh inserted in the system in month m	M head
ISC_m	Incomes from concentrate supplementation in month m	M R\$
$IS_{m,ks}$	Number of steers of age cohort ks inserted in the system in month m	M head
ISP_m	Income from protein supplementation in month m	M R\$
$LUC_{t,i,j}$	Land use change (or pasture restoration) from i to j in year t	M ha
$LU_{t,j}$	Land use j in year t	M ha
NBC_m	Number of new born calves in month m	M head
PC_m	Number of purchased cows in month m	M head
$PFFP_m$	Pasture forage intake by protein supplemented steers in month m	M t.(M head) ⁻¹
$PFSC_m$	Pasture forage intake by concentrate supplemented steers in month m	M t.(M head) ⁻¹
$PH_{m,kh}$	Number of purchased heifers of age cohort kh in month m	M head
PSC_t	Quantity of beef produced from concentrate supplemented steers in year t	M t
$PS_{m,ks}$	Number of purchased steers of age cohort ks in month m	M head
PSP_t	Amount of beef produced from protein supplemented steers in year t	M t
$RFSC_{m,c}$	Amount of crop c required for concentrate supplemented steers in month m	M t
$RFSP_{m,c}$	Amount of crop c required for protein supplemented steers in month m	M t
$RPA_{t,p}$	Removed area from pasture p in year t	M ha

SC_m	Number of steers supplemented with concentrate in month m	M head
$SCP_{m,c}$	Stored amount of crop c in month m	M t
SCV_m	Number of stocked calves in month m	M head
$SCW_{m,kc}$	Number of stocked cows in breeding stage kc in month m	M head
SF_m	Number of stocked steers under feedlot system in month m	M head
SHB_m	Number of selected heifers for breeding in month m	M head
$SH_{m,kh}$	Number of stocked heifers of age cohort kh in month m	M head
$SP_{m,kp}$	Number of steers of category kp supplemented with protein in month m	M head
SSC_m	Number of steers selected for concentrate supplementation in month m	M head
$SSF_{m,k}$	Number of steers selected to feedlot in month m	M head
$SS_{m,ks}$	Number of stocked steers of age cohort ks in month m	M head
SSP_m	Number of steers selected for protein supplementation in month m	
TDM_m	Amount of dry minter transferred from month m to month $m+1$	M t
UC	Used money from own capital	M R\$
WC_m	Number of weaned calves in month m	M head

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914 List of parameters

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Symbol	Description	Unit
General coefficients		
$A_{o,j}$	Initial area of land use j	M ha
BD_t	Beef demand in year t	M t
c_{ins}	Cost of insemination	R\$.head ⁻¹
c_{salt}	Cost of mineral salt	R\$.t ⁻¹
DA_t	Exogenous deforestation	M ha

dmi_{CV}	Dry-matter intake of calves	$\text{Kg.head}^{-1}.\text{mth}^{-1}$
dmi_{kc}	Dry-matter intake of cows of breeding stage kc	$\text{Kg.head}^{-1}.\text{mth}^{-1}$
dmi_{kh}	Dry-matter intake of heifers of age cohort kh	$\text{Kg.head}^{-1}.\text{mth}^{-1}$
dmi_{ks}	Dry-matter intake of steers of age cohort ks	$\text{Kg.head}^{-1}.\text{mth}^{-1}$
DM_o	Initial pasture productivity	t.ha^{-1}
fc	Fixed costs per pasture area	$\text{R}.\text{ha}^{-1}.\text{mth}^{-1}$
ir	Savings interest rate	$\%.\text{yr}^{-1}$
mc_{CV}	Maintenance cost of calves	$\text{R}.\text{head}^{-1}.\text{mth}^{-1}$
mch_{kh}	Maintenance cost of heifers of age cohort kh	$\text{R}.\text{head}^{-1}.\text{mth}^{-1}$
mc_{kc}	Maintenance cost of cows of breeding stage kc	$\text{R}.\text{head}^{-1}.\text{mth}^{-1}$
$mc_{S_{ks}}$	Maintenance cost of steers of age cohort ks	$\text{R}.\text{head}^{-1}.\text{mth}^{-1}$
oc_{Max}	Available own capital	M R\$
prc_{kc}	Price of cows in breeding stage kc	$\text{R}.\text{head}^{-1}.\text{mth}^{-1}$
prh_{kh}	Price of heifer of age cohort kh	$\text{R}.\text{head}^{-1}.\text{mth}^{-1}$
$prod_{p,CM}$	Dry-minter productivity of pasture p in the calendar month CM	$\text{t.ha}^{-1}.\text{mth}^{-1}$
prs_{ks}	Price of steers of age cohort ks	$\text{R}.\text{head}^{-1}.\text{mth}^{-1}$
tc	Cattle trading cost	$\text{R}.\text{head}^{-1}$
α	Adjustment parameter for the end of production	dimensionless
γ_{CC}	Cull cow carcass yield	dimensionless
γ_H	Heifer carcass yield	dimensionless
γ_S	Steer carcass yield	dimensionless
ζ	Ratio of herbage mass loss due to grazing (grazing efficiency)	dimensionless
μ_{CV}	Calf mortality rate	dimensionless
μ_{CW}	Cow mortality rate	dimensionless
μ_{kh}	Mortality rate of heifers of age cohort kh	dimensionless
μ_{ks}	Mortality rate of steers of age cohort ks	dimensionless
$\sigma_{CM(m)}$	Ratio of herbage mass loss due senescence	dimensionless

$\tau_{CM(m)}$	Minimum herbage mass (dry minter) transference in month CM(m)	$t.ha^{-1}.mth^{-1}$
ψ	Fraction of feedlot steers in relation to the total slaughtered animals	dimensionless
ω_{CC}	Weight of cull cows	kg
ω_S	Weight of steers finished under pasture	kg
ω_H	Weight of heifers finished under pasture	kg

Pasture restoration coefficients

$INA_{i,j}$	Amount applied of input (or service) <i>inp</i> on land use (or pasture restoration) from land use <i>i</i> to <i>j</i>	$kg.ha^{-1}$
$c_{i,j}$	Cost of land use change (or pasture restoration)	$R\$.ha^{-1}$
$NA_{i,j}$	Nitrogen application on land use change (or pasture restoration) from land use <i>i</i> to <i>j</i>	$kg.ha^{-1}$

Feedlot finishing coefficients

dmi_{FL}	Dry-matter intake of feedlot steers	$Kg.head^{-1}.mth^{-1}$
nfc_{FL}	Non feed costs of feedlot finishing	$R\$.head^{-1}.mth^{-1}$
pr_{FL}	Selling price of feedlot steers	$R\$.head^{-1}.mth^{-1}$
$prr_{c,FL}$	Fraction of crop <i>c</i> in the feedlot ration composition	dimensionless
$prr_{salt,FL}$	Proportion of mineral salt in feedlot ration	%
γ_{FL}	Feedlot steer carcass yield	dimensionless
μ_{FL}	Mortality rate of feedlot steers	dimensionless
ω_{FL}	Weight of steers finished under feedlot	kg

Supplementation concentrate coefficients

c_{urea}	Cost of mineral urea	$R\$.kg^{-1}$
dmi_{SC}	Steers' dry-matter intake of concentrate supplementation	$kg.head^{-1}.mth^{-1}$
mc_{SC}	Maintenance cost of supplemented concentrate steers	$R\$.head^{-1}.mth^{-1}$
nfc_{SC}	Non feed costs of supplementation concentrate	$R\$.head^{-1}.mth^{-1}$
$pdmi_{SC}$	Forage dry matter intake of concentrate supplemented steers	$R\$.kg^{-1}.mth^{-1}$
$prr_{c,SC}$	Proportion of crop <i>c</i> in the concentrate supplement	dimensionless

$pr_{salt,SC}$	Proportion of mineral salt in concentrate supplement	dimensionless
$pr_{Urea,SC}$	Proportion of urea in concentrate supplement	dimensionless
pr_{SC}	Selling price of steers finished under supplementation concentrate	R\$.head ⁻¹
γ_{SC}	Carcass yield of concentrate supplemented steers	dimensionless
μ_{SC}	Mortality rate of supplemented concentrate steers	dimensionless
ω_{CS}	Finishing weight of Concentrate supplement steer	kg

Supplementation protein coefficients

$dmi_{SP,kp}$	Dry-matter intake of concentrate supplementation of steer of age cohort kp	kg.head ⁻¹ .mth ⁻¹
mSP_{kp}	Maintenance cost of supplemented protein steer of age cohort kp	R\$.head ⁻¹ .mth ⁻¹
nfc_{SP}	Non feed costs of supplementation protein	R\$.head ⁻¹ .mth ⁻¹
$pdmi_{kp}$	Forage dry matter intake of concentrate supplemented steers of age cohort kp	kg.head ⁻¹ .mth ⁻¹
$pr_{c,SP}$	Proportion of crop c in the protein ration	dimensionless
$pr_{NaCl,SP}$	Proportion of NaCl in protein ration	dimensionless
$pr_{salt,SP}$	Proportion of mineral salt in protein ration	dimensionless
$pr_{urea,SP}$	Proportion of urea in protein ration	dimensionless
pr_{SP}	Price of steer of age cohort kp supplemented with protein	R\$.head ⁻¹
γ_{SP}	Carcass yield of protein supplemented steers	dimensionless
μ_{kp}	Mortality rate of supplemented protein steers of age cohort kp	dimensionless
ω_{kp}	Weight of protein supplemented steer of age cohort kp	kg

Nitrification inhibitors coefficients

c_{NIH}	Cost of nitrification inhibitors	R\$.kg ⁻¹
cv_{N,N_2O}	Conversion factor of N into N ₂ O	dimensionless
p_{NIH}	Nitrification inhibitors efficiency	dimensionless
a_{NIH}	Nitrification inhibitors application (proportional to N application)	dimensionless
RL	Proportion of N saved by using nitrification inhibitors	dimensionless

GHG emissions coefficients

ce_m	Total cattle emissions (in the baseline)	$\text{Kg CO}_2\text{e.mth}^{-1}$
$ce_{m,SC}$	Total cattle emissions from concentrate supplemented steers	$\text{Kg CO}_2\text{e.mth}^{-1}$
$ce_{m,SC}$	Total cattle emissions from protein supplemented steers	$\text{Kg CO}_2\text{e.mth}^{-1}$
$cs_{t,j}$	Soil organic carbon stock under land use j in year t	Mt C
$cv_{N \rightarrow N_2O}$	Conversion factor of N to N_2O	dimensionless
de_t	Total natural vegetation emissions	$\text{Mt CO}_2\text{e.yr}^{-1}$
ec_{kc}	Emission factor of cow of age cohort kh	$\text{Kg CO}_2\text{e.head}^{-1}$ $^1.\text{mth}^{-1}$
e_{CV}	Emissions factor of calves	$\text{Kg CO}_2\text{e.head}^{-1}$ $^1.\text{mth}^{-1}$
e_{FL}	Emissions factor of feedlot steers	$\text{Kg CO}_2\text{e.head}^{-1}$ $^1.\text{mth}^{-1}$
eh_{kh}	Emission factor of heifer of age cohort kh	$\text{Kg CO}_2\text{e.head}^{-1}$ $^1.\text{mth}^{-1}$
es_{ks}	Emission factor of steer of age cohort ks	$\text{Kg CO}_2\text{e.head}^{-1}$ $^1.\text{mth}^{-1}$
fe_t	Total N-based fertilizers emissions (without nitrification inhibitors)	$\text{Mt CO}_2\text{e.yr}^{-1}$
$fe_{t,NIH}$	Total N-based fertilizers emissions (with nitrification inhibitors)	$\text{Mt CO}_2\text{e.yr}^{-1}$
r	Carbon respiratory losses parameter	dimensionless
$\Delta cs_{t,j}$	Amount of carbon sequestration under land use j in year t	Mt C.yr^{-1}
ε_j	Carbon equilibrium stock under land use j	t.ha^{-1}
θ	Natural vegetation above ground biomass	t C.ha^{-1}
σ	Natural vegetation below ground biomass	t C.ha^{-1}

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919 Max $CASH_M$ (1)

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922 S.t:

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925 $LU_{t,j} = A_{o,j} \forall j$ (2)

926

$$LU_{t,p} = LU_{t-1,p-\hat{\delta}(t)} + \sum_i (LUC_{t,i,p} - LUC_{t-1,p-\hat{\delta}(t),i}) - RPA_{t,p}$$

927 $t > 1, p \neq C$ (3)

928

$$LU_{t,p} = LU_{t-1,p-\hat{\delta}(t)} + \sum_i (LUC_{t,i,p} - LUC_{t-1,p-\hat{\delta}(t),i}) + DA_t + EDA_t - RPA_{t,p}$$

929 $t > 1, p = C$

930 (4)

931

$$LU_{t,c} = \sum_i LUC_{t,i,c}, \quad t > 1$$

932 (5)

933

$$\sum_j LUC_{t,p,j} + RPA_{t,p} \leq LU_{t-1,p}, \quad t > 1$$

934 (6)

935

$$\sum_j LUC_{t,c,j} \leq LU_{t-1,c}, \quad t > 1$$

936 (7)

937

$$SS_{m,ks} = IS_{m,ks} + (1 - \mu_{ks})SS_{m-1,ks} + \sum_r \prod_{i=1}^r (1 - \mu_{ks-i})^3 IS_{m-3r,ks-r} -$$

$$- \sum_r \prod_{i=1}^r (1 - \mu_{ks+1-i})^3 IS_{m-3r,ks-r+1}, \quad \forall m, ks < 9, \quad r \in \{1, 2, \dots\}$$

938

939 (8)

940

$$SS_{m,ks} = \sum_r \prod_{i=1}^r (1 - \mu_{ks-i})^3 IS_{m-3r,ks-r}, \forall m, ks = 9, r \in \{1,2,\dots\}$$

941

942 (9)

943

$$IS_{m,ks} = 0.5WC_m + PS_{m,ks}, \forall m, ks = 1 \quad (10)$$

944

$$IS_{m,ks} = PS_{m,ks} - SSF_m, \forall m, ks = 7 \quad (11)$$

946

$$IS_{m,ks} = PS_{m,ks}, \forall m, ks > 1 \wedge ks \neq 7 \quad (12)$$

947

$$SH_{m,kh} = IH_{m,kh} + (1 - \mu_{kh})SH_{m-1,ks} + \sum_r \prod_{i=1}^r (1 - \mu_{ks-i})^3 IH_{m-3r,ks-r} -$$

$$- \sum_r \prod_{i=1}^r (1 - \mu_{kh+1-i})^3 IH_{m-3r,kh-r+1}, \forall m, kh < 9, r \in \{1,2,\dots\}$$

950

951 (13)

952

$$SH_{m,kh} = \sum_r \prod_{i=1}^r (1 - \mu_{kh-i})^3 IH_{m-3r,kh-r}, \forall m, kh = 9, j \in \{1,2,\dots\}$$

953

954 (14)

955

$$IH_{m,kh} = 0.5WC_m + PH_{m,kh}, \forall m, kh = 1 \quad (15)$$

956

$$IH_{m,kh} = PH_{m,kh} - SHB_m, \forall m, kh = 7 \quad (16)$$

957

$$IH_{m,kh} = PH_{m,kh}, \forall m, kh > 1 \wedge kh \neq 7 \quad (17)$$

958

$$SCW_{m,kc} = (1 - \mu_{CW})SCW_{m-1,kc} + IC_m - IC_{m-9}, \forall m, kc = 1 \quad (18)$$

959

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963

964 $SCW_{m,kc} = (1 - \mu_{CW})^{15+18*3} IC_{m-(15+18*3)}, \forall m, kc = 12$ (19)

965

966 $SCW_{m,kc} = (1 - \mu_{CW})SCW_{m-1,kc} + (1 - \mu_{CW})^{18ord(kc)} IC_{m-18ord(kc)} -$
 $-(1 - \mu_{CW})^{9+18ord(kc)} IC_{m-(9+18ord(kc))}, \forall m, kc \in P = \{4,7,10\}$

967 (20)

968

969 $SCW_{m,kc} = (1 - \mu_{CW})SCW_{m-1,kc} + (1 - \mu_{CW})^{9+18(ord(kc)-1)} IC_{m-(9+18(ord(kc)-1))} -$
 $-(1 - \mu_{CW})^{15+18(ord(kc)-1)} IC_{m-(15+18(ord(kc)-1))}, \forall m, kc \in L = \{2,5,8,11\}$
 970 (21)

971

972 $SCW_{m,kc} = (1 - \mu_{CW})SCW_{m-1,kc} + (1 - \mu_{CW})^{15+18(ord(kc)-1)} IC_{m-(15+18(ord(kc)-1))} -$
 $-(1 - \mu_{CW})^{18+18(ord(kc)-1)} IC_{m-(18+18(ord(kc)-1))}, \forall m, kc \in N = \{3,6,9\}$
 973 (22)

974

975 $IC_m = PH_m + SHB_m, \forall m$ (23)

976

977 $NBC_m = \sum_{i=0}^3 IC_{m-(9+18i)}, \forall m$ (24)

978

979 $SCV_m = (1 - \mu_{CV})SCV_{m-1} + NBC_m - (1 - \mu_{CV})^6 NBC_{m-6}, \forall m$
 980 (25)

981

982 $WC_m = (1 - \mu_{CV})^6 NBC_{m-6}, \forall m$ (26)

983

984 $FSF_m = (1 - \mu_{FL})^2 SSF_{m-2}, \forall m$ (27)

985

986 $SF_m = (1 - \mu_{FL})SF_{m-1} + SSF_m - FSF_m, \forall m$ (28)

987

988

$$\sum_{m/\left\lfloor \frac{m}{12} \right\rfloor = t} FSF_m = \psi \left(\sum_{m/\left\lfloor \frac{m}{12} \right\rfloor = t} (SS_{m,9} + SH_{m,9} + FSF_m + SCW_{m,12}) \right), \forall t$$

989

990 (29)

991

$$(1 + \zeta) \left(\sum_{ks} dmi_{ks} SS_{m,ks} + \sum_{kh} dmi_{kh} SH_{m,kh} + \sum_{kc} dmi_{kc} SCW_{m,kc} + dmi_{CV} SCV_m \right) + TDM_m$$

=

$$\sum_p prod_{p,CM(m)} LU_{t(m),p} + (1 - \sigma_{CM(m)}) TDM_{m-1} \leq 0, \quad 1 < m \leq M$$

992

993 (30)

994

995

$$\tau_{CM(m)} \sum_p LU_{t,p} - TDM_m \leq 0, \quad \forall m$$

996

(31)

997

$$SCP_{m,c} = SCP_{m-1,c} + prod_{c,CM(m)} LU_{t(m),c} - prr_{c,FL} dmi_{FL} SF_m, \quad \forall c, \forall m$$

998

999 (32)

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1002

$$\sum_{m/\left\lfloor \frac{m}{12} \right\rfloor = t} (\gamma_S \omega_S SS_{m,ks=9} + \gamma_H \omega_H SH_{m,kh=9} + \gamma_C \omega_C SCW_{m,kc=12} + \gamma_{FL} \omega_{FL} FSF_m) = BD_t, \quad \forall t$$

1003

1004 (33)

1005

$$CIN_m = prs_9 SS_{m,9} + prh_9 SH_{m,9} + pr_{FL} FSF_m + prc_{12} SCW_{m,12}, \quad \forall m$$

1006

1007 (34)

1008

$$\begin{aligned}
COT_m = & fc \sum_p LU_{t,p} + \sum_{ks=1}^8 (tc + prs_{ks}) PS_{m,ks} + \sum_{kh=1}^8 (tc + prh_{kh}) PH_{m,kh} + (tc + prc_1) PC_m + \\
& + \sum_{ks} mcs_{ks} SS_{m,ks} + \sum_{kh} mch_{kh} SH_{m,kh} + \sum_{kc} mc_{kc} SCW_{m,ks} + mc_{CV} SCV_m + \\
& + (nfc_{FL} + c_{salt} prr_{salt,FL} dmi_{FL})(SF_m + FSF_m) + c_{ins} SHB_m + LI_m \sum_i \sum_j c_{i,j} LUC_{t(m),i,j} , \forall m
\end{aligned}
\tag{35}$$

1009
1010

$$CASH_m = UC + CIN_m - COT_m , m = 1 \tag{36}$$

1011
1012

$$UC \leq oc_{max} \tag{37}$$

1013
1014

$$CASH_m = CASH_{m-1} + CIN_m - COT_m , m > 1 \tag{38}$$

1015
1016

$$\begin{aligned}
CASH_m = & CASH_{m-1} + CIN_m - COT_m - (1 + ir)^T UC + \\
& + \alpha \left(\sum_{ks=1}^8 prs_{ks} SS_{m,ks} + \sum_{kh=1}^8 prh_{kh} SH_{m,kh} + prc_{kc} \sum_{kc} SCW_{m,kc} \right)
\end{aligned}$$

1017
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$$m = M \tag{39}$$

1019
1020

$$FSC_m = (1 - \mu_{SC})^2 SSC_{m-2} , \forall m \tag{40}$$

1021
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1023

$$SC_m = (1 - \mu_{SC}) SC_{m-1} + SSC_m - FSC_m , \forall m \tag{41}$$

1024
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1027

$$PSC_t = \sum_{m \mid \left\lfloor \frac{m}{12} \right\rfloor = t} \gamma_{SC} \omega_{SC} FSC_m , \forall t \tag{42}$$

1028

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1030

$$\begin{array}{l} 1031 \\ 1032 \end{array} \quad CSC_m = ((c_{urea} prr_{urea,SC} + c_{salt} prr_{salt,SC}) dmi_{SC} + nfc_{SC} + mc_{SC}) SC_m, \forall m \quad (43)$$

1033

$$1034 \quad ISC_m = pr_{SC} FSC_m, \forall m \quad (44)$$

1035

$$1036 \quad PFSC_m = (1 + \xi) pdmi_{SC} SC_m, \forall m \quad (45)$$

1037

$$1038 \quad RFSC_{m,c} = prr_{c,SC} dmi_{SC} SC_m, \forall c, \forall m \quad (46)$$

1039

$$\begin{array}{l} 1040 \\ 1041 \end{array} \quad SP_{m,kp} = (1 - \mu_{kp}) SP_{m-1,kp} + SSP_m - (1 - \mu_{kp})^3 SSP_{m-3,kp}, kp = 1, \forall m \quad (47)$$

1042

$$\begin{array}{l} 1043 \\ 1044 \end{array} \quad SP_{m,kp} = (1 - \mu_{kp}) SP_{m-1,kp} + \prod_{r=1}^{kp-1} (1 - \mu_r)^3 SSP_{m-3(kp-1)} - \prod_{r=1}^{kp} (1 - \mu_r)^3 SSP_{m-3kp}, kp > 1, \forall m \quad (48)$$

1045

1046

$$1047 \quad PSP_t = \sum_{m \mid \left\lfloor \frac{m}{12} \right\rfloor = t} \gamma_{SP} \omega_{kp} SP_{m,kp}, kp = 6, \forall t \quad (49)$$

1048

1049

$$\begin{array}{l} 1050 \\ 1051 \end{array} \quad \begin{aligned} CSP_m &= (c_{urea} prr_{urea,SP} + c_{salt} prr_{salt,SP} + c_{NaCl} prr_{NaCl,SP}) \sum_{kp} dmi_{SP,kp} SP_{m,kp} + \\ &+ \sum_{kp} (nfc_{SP} + msp_{kp}) SP_{m,kp}, \forall m \end{aligned} \quad (50)$$

1052

1053

1054 $ISP_m = pr_{kp} SP_{m,kp}, kp = 6, \forall m$ (51)

1055

1056 $PFSP_m = (1 + \xi) \sum_{kp} pdmi_{kp} SP_{m,kp}, \forall m$ (52)

1057

1058 $RFSP_{m,c} = prr_{c,SP} \sum_{kp} dmi_{SP,kp} SP_{m,kp}, \forall c, \forall m$ (53)

1059

1060 $CNIH_m = c_{NIH} a_{NIH} (1 - RL) \sum_i \sum_j NA_{i,j} LUC_{t(m),i,j} LI_m$ (54)

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1067 **Objective function**

1068

1069 **Eq. 1** corresponds to the maximization of cash/income at the last month of
 1070 production (month M), i.e., gross margin. $CASH_M$ (M R\$) represents cash at
 1071 the very last month (M) of production. **Eq. 1** is equivalent to the expanded
 1072 equivalent **Eq. 39**.

1073

1074 **Land use dynamics**

1075

1076 **Eq. 2** is responsible for allocating the initial land use of pastures types
 1077 $\{A,B,C,D,E,F\}$ and crops $\{Corn(silage),Corn(grain),Soybeans\}$. $LU_{t,j}$ (M
 1078 ha) accounts for the allocated area of land use/pasture types j in year t , Ao,j
 1079 represents the initial allocation of each land use/pasture types.

1080

1081 **Eq. 3** represents the pasture allocation, allowing for degradation, pasture
1082 restoration and land use change decisions. As degradation was assumed to
1083 occur biannually, the binary parameter vector $\delta(t)$ is used as an index as
1084 follows:

1085

$$\delta(t) = \begin{cases} 1, & \text{if } t \text{ is an odd number} \\ 0, & \text{if } t \text{ is even} \end{cases}$$

1086

1087 The area of pasture p in year t ($LU_{t,p}$) is given by the area of pasture p in the
1088 previous year $t-1$ ($LU_{t-1,p}$) or the area pasture $p-1$ ($LU_{t-1,p-1}$) if t is a year
1089 where degradation occurs, i.e., t is an odd number, plus the area from other

1090 land uses/pasture types i to pasture p in year t ($\sum_i LUC_{t,i,p}$), less the area
1091 converted from pasture p to the other land uses/pasture types i ($\sum_i LUC_{t,p,i}$), subtracted from the area of pasture p removed in year t

1092 ($RPA_{t,p}$).

1094

1095

1096 **Eq. 4** is identical to **Eq. 3** except for land expansion (endogenous and
1097 exogenous), which is allocated to pasture $p=C$ (due to equivalence of
1098 natural vegetation productivity with pasture level C). DA_t represents the
1099 exogenous pasture expansion and EDA_t the exogenous expansion term, i.e.,
1100 extra deforestation required to meet demand in year t .

1101

1102 **Eq. 5** expresses the crop allocation, which is a simpler dynamic than
1103 pasture: every year crops need to be planted and harvested. **Eq. 5** says the
1104 area of crop c in year t is equivalent to the sum of converted (or re-planted

1105 in the case of $i=c$) area from all possible land uses to crop c ($\sum_i LUC_{t,i,c}$).

1106

1107 **Eq. 6** and **Eq. 7** are used to constrain the land use change variables
1108 according to the available area, respectively for pastures and crops. **Eq. 6**
1109 says the area converted from pasture p to improved pastures (restoration) or
1110 to crops in year t , (first term in the right-hand side (RHS)), has to be no
1111 greater than the available area in the previous year $t-1$, i.e., $LU_{t-1,p} - RPA_{t,p}$.
1112 **Eq. 7** is similar to **Eq. 6** but for crops (unlike pasture, it is assumed no crop
1113 area is removed).

1114

1115

1116

1117

1118 **Grazing steer dynamics**

1119

1120 **Eq. 8** models the steer fattening until slaughter weight – represented as the
1121 transfer from age cohorts $ks-1$, $ks-2$, $ks-3$,... to ks . The number of steers (M
1122 heads) in the system in time step (month) m ($SS_{m,ks}$) is given by the
1123 combination of 4 terms: (i) the number of steers that were inserted in the
1124 system in that month ($IS_{m,ks}$); (ii) the number of steers ks in the previous
1125 month less the mortality rate (second term in the RHS); (iii) the number of
1126 steers that are changing from the previous age cohorts to ks (third term in
1127 the RHS), and (iv) the number of steers that are changing from ks to the next
1128 cohort $ks+1$ (fourth term in the RHS). (i) and (ii) are straightforward; (iii) is
1129 given by the number of steers that were inserted in the system as age cohort
1130 $ks-1$ three months before month m , plus the number inserted 6 months
1131 before as category $ks-2$ and so forth (every 3 months steers change to the
1132 next age cohort), i.e., $IS_{m-3,ks-1} + IS_{m-6,ks-2} + IS_{m-9,ks-3} + IS_{m-12,ks-4} + \dots =$

1133 $\sum_r IS_{m-3r,ks-r}$, the term multiplying $IS_{m-3r,ks-r} \left(\prod_{i=1}^r (1 - \mu_{ks-i})^3 \right)$ accounts

1134 for accumulated transfer rate according to mortality rate for each element in

1135 the sum (cubed because the mortality rate is a monthly value); (iv) is
1136 analogous to (iii).

1137

1138 **Eq. 9** accounts for the number of finished steers, i.e., age cohort 9. In that
1139 cohort there is no monthly transfer from the same cohort, i.e., once a steer
1140 reach age cohort 9, it is slaughtered.

1141

1142 **Eq. 10** accounts for the number of steers of the first age cohort inserted into
1143 the system (calves) in month m ($IS_{m,ks=1}$). An animal can be inserted into the
1144 grazing system by: (i) breeding: i.e., a calf is born in the system (first term
1145 in the RHS) or (ii) by being purchased (second variable on the RHS). Let
1146 WC_m be the number of newborn calves in month m and $PS_{m,ks}$ the number of
1147 calves purchased in that month. It is assumed half of the animals born are
1148 males and half females; thus WC_m is multiplied by 0.5.

1149

1150 **Eq. 11** says the number of inserted steers of age cohort $ks=7$ is given by the
1151 number of purchased steers ($PS_{m,ks=7}$) less the number of steers allocated
1152 into feedlot systems (SSF_m).

1153

1154 **Eq. 12** says that the number of inserted steers of age cohort $ks\neq 7$ equals the
1155 number of purchased steers.

1156

1157

1158 **Grazing heifer dynamics**

1159

1160

1161 Heifers are finished under the grazing system as occurs with steers, or
1162 selected to become cows, and thus generate calves in the system.

1163

1164 Let $SH_{m,kh}$ represents the number of heifer of age cohort kh in month m ;
 1165 $IH_{m,kh}$ the number of heifers kh inserted in the system in month m ; $PH_{m,kh}$,
 1166 the number of heifers purchased in month m and SHB_m the number of
 1167 heifers selected for breeding in that month. Then **Eq. 13 - 17** are
 1168 respectively analogous to Eq. **8 - 12**, but for heifers. Heifers cannot be
 1169 moved to feedlot systems in the same way as steers, instead heifers of age
 1170 cohort $kh=7$ can be selected for breeding process (variable SHB_m in **Eq. 16**)
 1171 and then added to the cow-calf equation dynamics (**Eq. 23**).

1172

1173 **Breeding dynamics**

1174

1175

1176 Each cow generates one calf per cycle, a cycle is composed of three
 1177 breeding stages: (i) pregnant stage, (ii) lactation stage, and (ii) non-lactation
 1178 stage. After four cycles, cows are removed from breeding process and
 1179 slaughtered (cull cows). The cycles correspond to cow transfer from
 1180 breeding stage $kc=1$ up to $kc=12$:

1181

1182

1183 Extended Table 9: Breeding stages

Breeding stage (kc)	Description	Duration (months)
1	1st pregnancy	9
2	1st lactation	6
3	1st non-lactation	3
4	2nd pregnancy	9
5	2nd lactation	6
6	2nd non-lactation	3
7	3rd pregnancy	9

8	3rd lactation	6
9	3rd non-lactation	3
10	4th pregnancy	9
11	4th lactation	6
12	4th non-lactation (cull cow)	1

1184

1185 As for the steer and heifer dynamics, the number of cows in the system
1186 (stocked cows) is given by the transfer of previous categories (or age
1187 cohorts).

1188

1189 **Eq. 18 - 22** represent the transfer across the breeding stages, starting from
1190 1st pregnancy ($kc=1$) until the last stage ($kc=12$) when cows are removed
1191 from the breeding system.

1192

1193 **Eq. 18** says that the number of cows in the initial breeding stage ($kc=1$) in
1194 month m ($SCW_{m,ks}$) is given by the number of cows in stage kc in $m-1$, less
1195 the mortality rate μ_{CW} (first term in the RHS), plus the cows that are inserted
1196 into the breeding system in that month (IC_m), less the cows leaving stage
1197 $kc=1$, i.e., cows that entered the system 9 months before m (IC_{m-9}).

1198

1199 **Eq. 19** says the number of cows in the last breeding stage ($SCW_{m,kc=12}$) is
1200 given by the number of cows inserted in the system 4 cycles before, i.e.,
1201 $IC_{m-(15+18*3)}$. The first 3 cycles are comprised of 9 months of pregnancy, 6
1202 months of lactation and 3 months resting, totaling 18 months, the last cycle
1203 does not include the resting stage, i.e., pregnancy +lactation, totaling 15
1204 months.

1205

1206 **Eq. 20** represents the dynamics of cows in the pregnancy breeding stages
1207 (for $kc > 1$), i.e for $kc \in P = \{4,7,10\}$, where P is the set of indexes of cows in
1208 the pregnancy breeding stage. Here, the number of cows in month m
1209 ($SCW_{m,kc}$) is given by the number in the previous month less the mortality
1210 rate (first term in the RHS), plus the cows inserted in the system one cycle
1211 before for $kc=4$, two cycles before for $kc=7$ and 3 cycles before for $kc=10$,
1212 i.e., cows inserted in $ord(kc)*18$ months before month m ($IC_{m-18ord(kc)}$). The
1213 term $(1 - \mu_{CW})^{18ord(kc)}$ is the accumulated mortality rate. Similarly, the number
1214 of cows moving from the pregnancy stages to the lactation stages in month
1215 m is equivalent the number of cows that were inserted as in the second term
1216 in the RHS, but 9 months before m , i.e., $IC_{m-(9+18ord(kc))}$.

1217

1218

1219 **Eq. 21** and **22** follow the same logic of **Eq. 20** but represent the number of
1220 cows in lactation ($kc \in L = \{2,5,8,11\}$), and the number cows in non-
1221 lactation (or resting stage) ($kc \in N = \{3,9,6\}$), respectively.

1222

1223 **Eq. 23** indicates the number of cows inserted into the breeding process in
1224 month m (IC_m) given by the number of purchased (PH_m) plus the number
1225 of selected heifers (SHB_m).

1226

1227 **Eq. 24** accounts for the number of newborn calves in month m . Let NBC_m
1228 be the number of births in month m , then NBC_m is equivalent to the number
1229 of cows inserted into the breeding system at $m-9$, (one cow generates one
1230 calf) plus the number of cows inserted $m-18$ (duration of a cycle), and so

1231 forth, until it completes 4 cycles, i.e.,
$$\sum_{i=0}^3 IC_{m-(9+18i)}$$
.

1232

1233 **Eq. 25** accounts for the number of calves in the system. Let SCV_m be the
1234 number of calves in month m , it is then given by the transfer from $m-1$ (first

1235 term in the RHS), plus births in m (NBC_m), less the births at $m-6$ (NBC_{m-6}),
1236 since calves are fed by cows for 6 months, with all terms multiplied by
1237 respective monthly transfer with accumulated mortality rate, where μ_{CV}
1238 represents the monthly mortality rate for calves.

1239

1240 **Eq. 26** gives the number of weaned calves (WC_m) in month m , i.e., calves
1241 born in $m-6$, multiplied by accumulated transfer with mortality rate, $(1-$
1242 $\mu_{CV})^6 NBC_{m-6}$. The weaned calves are then allocated half to steers $ks=1$ and
1243 half to heifers $kh=1$, respectively to **Eq. 10** and **Eq. 15**.

1244

1245 **Feedlot finishing**

1246

1247 **Eq. 27** accounts for the number of finished steers under the feedlot system
1248 in month m (FSF_m). Once a steer is selected for the feedlot (from $ks=7$), it
1249 takes two months to slaughter. FSF_m is equivalent to the number of steers
1250 removed from grazing system (SSF_m), multiplied by the two-months
1251 accumulated age cohorts transfer rate $(1-\mu_{FL})^2$, where μ_{FL} is the monthly
1252 mortality rate of feedlot steers.

1253

1254 **Eq. 28** accounts for the number of steers in the feedlot (SF_m) - before
1255 slaughter. SF_m is given by the transfer from the previous month $(1-\mu_{FL})SF_{m-1}$,
1256 plus steers inserted into the feedlot in that month (SSF_m), less the
1257 slaughtered steers in that month (FSF_m).

1258

1259

1260 **Eq. 29** establishes the proportion of feedlot animals, i.e. the number of
1261 feedlot steers in year t has to be a proportion ψ of the total annual
1262 slaughtered cattle among grazing steers, feedlot steers, grazing heifers and
1263 discarded cows. $SS_{m,9}$ and $SH_{m,9}$ are the numbers of slaughtered animals
1264 (last age cohort) respectively for steers and heifers, $SCW_{m,12}$, the number of

1265 cull cows in month m . The sum over m such that $\left\lceil \frac{m}{12} \right\rceil = t$ (ceiling of $m = t$)
 1266 is used make the sum over the months of the equivalent year, i.e., if $t=1$ then
 1267 $m \in \{1,2,\dots,12\}$, if $t=2$ then $m \in \{13,14,\dots,24\}$ and so forth.

1268

1269

1270

1271 **Forage budgeting**

1272

1273

1274

1275 **Eq. 30** represents the feed budgeting of all grazing cattle, i.e., the balance of
 1276 demanded dry matter (terms in the left hand side (LHS)) and forage
 1277 availability (terms in the RHS). Let dmi_{ks} , dmi_{kh} , dmi_{kc} and dmi_{CV} be the dry
 1278 matter intake (in $\text{kg}\cdot\text{hd}^{-1}\cdot\text{mth}^{-1}$) of respectively steers of age cohort ks , heifer
 1279 of age cohort kh , cows in breeding stage kc , and calves. The total demanded
 1280 dry matter is given by the total consumed (the sums over the cohorts
 1281 indexes). Because there is loss of dry matter due to animal grazing, a
 1282 dimensionless parameter (ζ) is used to represent the dry matter losses
 1283 proportional to the total dry matter consumed, therefore total consumption is
 1284 multiplied by $(1 + \zeta)$. The model does not require that all available dry matter
 1285 has to be consumed in a given month, i.e., part of it can be transferred to the
 1286 next month by a variable representing the dry matter not consumed in month
 1287 m , TDM_m (slack variable). In the RHS of the inequality the available dry
 1288 matter in month m is represented. Let $prod_{p,CM(m)}$ be the dry matter
 1289 productivity ($\text{t}\cdot\text{ha}^{-1}\cdot\text{mth}^{-1}$) of pasture type p in the calendar month $CM(m)$,
 1290 thus the first term in the RHS represents the total dry matter produced in
 1291 month m . The available dry matter not consumed in month $m-1$ is
 1292 transferred to month m , less dry matter losses due to senescence process for
 1293 the equivalent calendar month ($\sigma_{CM(m)}$).

1294

1295 **Eq. 31** The slack variable TDM_m in **Eq. 30** has to be greater than a
1296 minimum value, i.e., not all the available dry matter (organic matter above
1297 ground) can be consumed by grazing cattle. Instead, there is a lower bound
1298 for TDM_m , i.e., a minimum of dry-matter per hectare that has to be
1299 transferred from one month to another, represented by $\tau_{CM(m)}$.

1300

1301

1302

1303 **Eq. 32** represents stocking of crops produced on the farm. Let $SCP_{m,c}$ be the
1304 amount of crop stocked in month m (M t), it is given by the stock from the
1305 previous month ($SCP_{m-1,c}$), plus the amount of crop c produced in month m
1306 (second term in the RHS), where $prodc_{,CM(m)}$ is the productivity of crop c in
1307 the calendar month $CM(m)$ (in $t.ha^{-1}$), less the amount of crop c that is
1308 consumed for ration formulation for feedlot cattle (third term in the RHS),
1309 where dmi_{FL} is the ration dry matter intake ($t.hd^{-1}.mth^{-1}$) of feedlot steers
1310 and $prr_{c,FL}$ is a dimensionless parameter representing the proportion of the
1311 intake that is obtained from crop c , i.e., proportion of crop c in the ration
1312 formulation.

1313

1314 **Beef demand**

1315

1316 **Eq. 33** is the demand constraint. Let $\gamma_S, \gamma_H, \gamma_C$ and γ_{FL} represent the carcass
1317 yield of grazing finished steers, heifers, cull cows and feedlot finished
1318 steers, respectively; and $\omega_S, \omega_H, \omega_C$ and ω_{FL} the finishing weight of grazing
1319 steers, heifers, cull cows and feedlot finished steers ($kg.hd^{-1}$), respectively.
1320 Total produced meat is equivalent to the product of carcass yield by finished
1321 weight and number of finished animals in month m of each category (then

1322 summed over the equivalent months of each year using the ceiling operator (
1323 $\lceil \cdot \rceil$), as in **Eq.29**).

1324

1325

1326 **Cash flow**

1327

1328

1329 **Eq. 34** represents farm incomes from the sale of finished animals. Let CIN_m
1330 be the farm incomes in month m , prs_g , prh_g , pr_{FL} and prc_{12} be the selling
1331 prices of finished grazing steers, heifers, finished feedlot steers and cull
1332 cows (R\$.hd⁻¹), respectively. Income is the product of cattle selling prices
1333 times the number of finished cattle, i.e., finished steers in month m ($SS_{m,9}$),
1334 heifers ($SH_{m,9}$), feedlot steers (FSF_m) and culled cows ($SCW_{m,12}$).

1335

1336 **Eq. 35** represents the costs of the farm in month m (COT_m), composed of:

1337 (i) fixed costs per pasture area (first term in the RHS), where fc is the cost

1338 per hectare, multiplied by the total area in year t ($\sum_p LU_{t,p}$); (ii) cost of
1339 purchasing animals, i.e, price and transactions costs (second to fourth term
1340 in the RHS), where pr_{ks} , pr_{kh} and $pr_{kc=1}$ are the purchasing price of steers

1341 of age cohort ks , heifers of age cohort kh and cows in breeding stage $kc=1$,

1342 (R\$.hd⁻¹)respectively; tc is a parameter representing the transaction cost per

1343 head. The summations ranges from 1 to 8 because $ks=9$ or $kh=9$ correspond

1344 to finished cattle; (iii) grazing cattle maintenance costs (from fifth to eighth

1345 term in the RHS), where mcs_{ks} , mch_{kh} , mc_{kc} and mc_{CV} are the maintenance

1346 costs per head for steers, heifers, cows and calves, respectively; (iv) feedlot

1347 non-feed costs (ninth term in the RHS), where nfc_{FL} is the maintenance cost

1348 for feedlot animals (R\$.hd⁻¹); c_{salt} is the cost of mineral salt used in ration

1349 formulation; $prr_{salt,FL}$ is a dimensionless parameter that represents the

1350 proportion of salt in the feedlot ration composition; (v) cost of inseminating

1351 heifers (tenth term in the RHS), where c_{ins} is the insemination cost per head;
1352 (vi) land use change and pasture restoration costs (last term in the RHS),
1353 where $c_{i,j}$ is the cost to restore one hectare of pasture i to improved pasture j
1354 (or the cost of changing one hectare from land use i to j). The land use
1355 change/restoration cost is always discounted in the first month for every
1356 year by using a binary parameter LI_m , where $LI_m = 1$ if $m=January$,
1357 otherwise $m=0$.

1358

1359 **Eq. 36** says the cash ($CASH_{m=1}$) in the first production month consists of
1360 own used capital (UC) plus incomes, less costs.

1361

1362 **Eq. 37** sets a constraint on used own capital availability, where oc_{max} is the
1363 available own capital.

1364

1365 **Eq. 38** says the subsequent monthly cash ($CASH_m$) (except the last month)
1366 is given by disposable cash from the previous month, plus incomes less
1367 costs.

1368

1369 **Eq. 39** represents the cash in the last month M (equivalent to gross margin).
1370 **(39)** is similar to **(38)**, but in the last month of production the model has to
1371 pay for the used capital UC , with a discount rate (ir) accumulated for T
1372 years (fourth term in the RHS). The last term in RHS represents the sale of
1373 the remaining animals in the system; i.e., the animals that did not achieve
1374 slaughter weight by the end of production. In this case, to avoid distortions
1375 in the solution, a calibration parameter α is used, this was determined such
1376 that the stocking rate kept approximately constant until the end of
1377 production (for fixed demand).

1378

1379

1380

1381

1382

1383

1384 **Concentrate supplementation**

1385

1386 **Eqs. 40 to 46** describe the supplementation concentrate measure, i.e., steer
1387 dynamics, intake and formulation of the supplement.

1388

1389 **Eqs. 40 and 41** are analogous to **eq. 27 and 28**, but for concentrate-
1390 supplemented steers, where FSC_m accounts for the number of steers finished
1391 under supplementation concentrate in month m ; μ_{SC} is the mortality rate of
1392 steers supplemented with concentrate; SSC_m represents the number of steers
1393 selected for concentrate supplementation (from age cohort $ks=8$); SC_m is the
1394 number of steers under concentrate supplementation in month m .

1395

1396 **Eq. 42** accounts for the beef produced under concentrate supplementation
1397 during year t (PSC_t): it is derived as the product of the number of steers
1398 times the finishing weight and carcass yield. Where γ_{SC} and ω_{SC} are the
1399 carcass yield and weight of steers finished under concentrate
1400 supplementation, respectively.

1401

1402

1403 **Eq. 43** represents the monthly costs of concentrate supplementation (CSC_m).
1404 The cost is proportional to the number of supplemented steers in month m
1405 (SC_m) and comprises the cost of mineral salt and urea contained in the
1406 supplement (term multiplying dmi_{SC}), where c_{urea} and c_{salt} represent the cost
1407 per kg of urea and mineral salt, respectively; dmi_{SC} is the dry matter
1408 supplement consumption ($\text{kg}\cdot\text{hd}^{-1}\cdot\text{mth}^{-1}$); nfc_{SC} and mc_{SC} are non-feed costs
1409 and animal maintenance costs from concentrate supplementation ($\text{R}\$\cdot\text{hd}^{-1}$
1410 $\cdot\text{hd}^{-1}\cdot\text{mth}^{-1}$).

1411

1412 **Eq. 44** expresses the income originating from concentrate supplemented
1413 steers (ISC_m), where pr_{SC} is the selling price of concentrated steers.

1414

1415 **Eq. 45** accounts for the forage intake of concentrate supplemented steers in
1416 month m ($PFSC_m$), where $pdmi_{SC}$ is the grass dry matter intake of
1417 concentrate supplemented steers (in $\text{t}\cdot\text{hd}^{-1}\cdot\text{mth}^{-1}$).

1418

1419 **Eq. 46** accounts for all the dry matter consumed from each crop contained
1420 in the concentrate supplement formulation in month m ($RFSC_{m,c}$), where
1421 $prr_{c,SC}$ is a dimensionless parameter that represents the proportion of crop c
1422 contained in concentrate formulation and dmi_{SC} is the concentrate dry matter
1423 intake (in $\text{t}\cdot\text{hd}^{-1}\cdot\text{mth}^{-1}$).

1424

1425 **Protein supplementation**

1426

1427 **Eq. 47-54** describes the protein supplementation dynamics.

1428

1429 **Eq. 47** represents the number of steers in the first age cohort of the category
1430 of protein supplemented steers. The number of steers for $kp=1$ in month m
1431 ($SP_{m,kp=1}$) is given by the number in $m-1$ ($SP_{m-1,kp=1}$) less the mortality rate
1432 (first term in the RHS), where μ_{kp} is the mortality rate for protein
1433 supplemented steers of age cohort kp , plus the animals selected to be fed by
1434 protein supplementation in month m (SSP_m , selected from $ks=1$), less the
1435 steers transferred to the next age cohort – after 3 months (third term in the
1436 RHS).

1437

1438 **Eq. 48** is similar to **eq. 47** but accounts for $kp>1$. The number of steers that
1439 are changing to age cohort kp in month m (second term in RHS) is given by
1440 the number of steers selected for protein supplementation 3 months before,

1441 plus the steers selected 6 months before, 9 months before and so on $= (I -$

1442 $\mu_{kp=1})^3 SSP_{m-3} + (I - \mu_{kp=1})^3 (I - \mu_{kp=2})^3 SSP_{m-6} + (I - \mu_{kp=1})^3 (I - \mu_{kp=2})^3 (I -$

1443 $\mu_{kp=3})^3 SSP_{m-9} = \prod_{r=1}^{kp-1} (1 - \mu_r)^3 SSP_{m-3(kp-1)}$. The third term in RHS is

1444 analogous but account for the number of steers that are changing from kp to

1445 the next age cohort $kp+1$.

1446

1447

1448 **Eqs. 49-53** are analogous to **eq. 42-46**, respectively. Where PSP_t is the meat

1449 produced from finished protein supplemented steers; γ_{SP} and ω_{SP} are the

1450 carcass yield and weight of finished protein supplemented steers,

1451 respectively; $SP_{m,kp}$ the number of steers under that supplementation in

1452 month m ; CSP_m the monthly total cost of supplementing steers with protein,

1453 where $pr_{urea,SP}$, $pr_{salt,SP}$ and $pr_{NaCl,SP}$ are the proportion of urea, mineral

1454 salt and NaCl contained in protein supplement formulation, respectively;

1455 $dmi_{SP,kp}$ is the protein supplementation consumed of steers age cohort kp

1456 ($\text{t}\cdot\text{hd}^{-1}\cdot\text{mth}^{-1}$); nfc_{SP} and $m_{sp,kp}$ are non-feed and maintenance costs for

1457 supplemented steers of age cohort kp ($\text{R}\$\cdot\text{hd}^{-1}\cdot\text{mth}^{-1}$); pr_{kp} is selling price of

1458 steers finished under protein supplementation (note that $kp=6$ is the finishing

1459 age cohort); and $pdmi_{kp}$ is the grass dry matter intake of steers age cohort

1460 kp .

1461

1462

1463 **Nitrification inhibitors**

1464

1465 **Eq. 54** expresses the monthly costs of nitrification inhibitors (C_{NIH_m}) –

1466 proportional to applied nitrogen. Let c_{NIH} be the cost of the kg nitrification

1467 inhibitor; a_{NIH} a dimensionless parameter representing application (kg of

1468 inhibitor per kg of N); RL is the proportion of N saved by using nitrification

1469 inhibitors (dimensionless); and $NA_{i,j}$ is the amount of N applied to convert

1470 one hectare of land use i to land use j . Thus, the double summations over i
 1471 and j account for all the applied N in year t ; LI_m (as in **Eq. 35**) is used to
 1472 discount the costs in the first month for every year ($LI_m = 1$ if $m=January$,
 1473 otherwise $m=0$).

1474

1475

1476 **GHG emissions accounting**

1477

1478 **Cattle emissions**

1479

1480 The equations below account for direct GHG emissions from cattle by
 1481 employing emissions factors.

1482

1483

$$ce_m = \sum_{ks} es_{ks} SS_{m,ks} + \sum_{kh} eh_{kh} SH_{m,kh} + \sum_{kc} ec_{kc} SCW_{m,kc} + e_{CV} SCV_m + e_{FL} (SF_m + FSF_m), \forall m$$

1484
 1485 (55)

1486

$$ce_{m,SC} = e_{SC} SC_m, \forall m$$

1487 (56)

1488

$$ce_{m,SP} = \sum_{kp} e_{kp} SP_{m,kp}, \forall m$$

1489 (57)

1490

1491

1492 **Eq. 55** accounts for the greenhouse gases emissions (in CO₂e) for each
 1493 cattle age cohort and feedlot steers, where ce_m is the total cattle emissions in
 1494 month m ; es_{ks} , eh_{kh} , ec_{kc} and e_{FL} are the emissions factors (in kg of
 1495 CO₂e.hd⁻¹.mth⁻¹) for steers of age cohort ks , heifers of age cohort kh , cows
 1496 in breeding stage kc and feedlot steers, respectively.

1497

1498

1499 **Eq. 56** and **eq. 57** account for concentrate and protein supplemented steer
1500 emissions, respectively, where e_{SC} and e_{kp} are the emissions factors (kg of
1501 $\text{CO}_2\text{e} \cdot \text{hd}^{-1} \cdot \text{mth}^{-1}$) of steers supplemented with concentrate and steers
1502 supplemented with protein, age cohort kp .

1503

1504 **Fertilization emissions**

1505

$$1506 \quad fe_t = 298cv_{N \rightarrow N_2O} \sum_j \sum_j NA_{i,j} LUC_{t(m),i,j} \quad (58)$$

$$1507 \quad fe_{t,NIH} = (1 - p_{NIH}) fe_t \quad (59)$$

1508

1509 **Eq. 58** accounts for the emissions from nitrogen (N) based fertilizers in year
1510 $t (fe_t)$. The term inside the sum gives the amount of N applied for all land
1511 use and pasture restoration options. The factor $cv_{N \rightarrow N_2O}$ corresponds to the
1512 proportion of N converted into N_2O ; and 298 is the N_2O equivalence in
1513 CO_2e - in global warming potential for 100 years (GWP-100).

1514

1515 **Eq. 59** accounts for the emissions from N-based fertilizers when nitrogen
1516 inhibitors are used, where in p_{NIH} represents the efficiency of nitrification
1517 inhibitors .

1518

1519

1520 **Deforestation emissions**

1521

$$1522 \quad de_t = \frac{11}{3} \theta (EDA_t + DA_t) \quad (60)$$

1523

1524 **Eq. 60** accounts for emissions from natural vegetation conversion into
 1525 pastures in year t (de_t), where EDA_t and DA_t represent the endogenous and
 1526 exogenous deforested area. Emissions are given by the product of the
 1527 deforested area multiplied by biomass above ground coefficient, θ (in
 1528 carbon per unit of area), converted to CO₂e by multiplying by 11/3.

1529

1530

1531 **Pasture emissions and carbon sequestration**

1532

1533 The equations below describe the pasture soil carbon dynamics.

1534

1535

$$\begin{aligned}
 cs_{t,p} &= cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} RPA_{t,p} + \\
 &+ \Delta cs_{t,p}, \forall t, p \neq C
 \end{aligned}$$

1536
 1537 (61)

1538

$$\begin{aligned}
 \Delta cs_{t,p} &= r \left(\varepsilon_p - \left(cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \right. \right. \\
 &\left. \left. - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} RPA_{t,p} \right) \right) LU_{t,p} \\
 &\forall t, p \neq C
 \end{aligned}$$

1539
 1540 (62)

1541

1542

$$\begin{aligned}
 cs_{t,p} &= cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} RPA_{t,p} + \\
 &+ \sigma(EDA_t + DA_t) + \Delta cs_{t,p}, \forall t, p = C
 \end{aligned}$$

1543
 1544 (63)

1545

1546

1547

$$\Delta cs_{t,p} = r \left(\varepsilon_p - \left(cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} LUC_{t,p} + \sigma(EDA_t + DA_t) \right) \right) LU_{t,p}$$

1548 $\forall t, p = C$
1549 (64)

1550

1551

$$cs_{t,c} = \sum_i \frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,c} + r \left(\varepsilon_c - \sum_i \frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,c} \right) LU_{t,c}$$

1552 $\forall t, \forall c$

1553 (65)

1554

1555

1556 **Eq. 61** describes the soil carbon accumulation for pastures levels except
1557 pasture $p=C$.

1558

1559 The amount of stocked carbon under pasture p in year t ($cs_{t,p}$) (in tonnes of
1560 carbon) is given by the carbon transferred from pasture $p-1$ (degradation) or
1561 the carbon transferred from pasture p itself, if no degradation occurs (first
1562 term in the RHS), as in **Eq. 3**. The second term in the RHS represents the
1563 transferred carbon from/to any other pasture or crops according to the land
1564 use change decision variables. We assume a proportional transfer of carbon
1565 per area of converted land use, e.g., if 100 ha of pasture F is restored to
1566 pasture A in year t , then the carbon in F has to be proportionally transferred

1567 to A , i.e., the amount of carbon per unit of area in F in $t-1$ $\left(\frac{cs_{t-1,F}}{LU_{t-1,F}} \right)$

1568 multiplied by $LUC_{t,FA} = 100$ ha is transferred to pasture A . The second term

1569 inside the sum is analogous but accounts for the carbon that is transferred

1570 from pasture p to other improved pasture or crops. The third term in RHS is
 1571 responsible for removing carbon when pasture area ($RPA_{t,p}$) is removed
 1572 from pasture level p in year t . The last term on the RHS represents the
 1573 carbon sequestration rate.

1574

1575 **Eq. 62** describes the carbon sequestration rate under pasture p in year t
 1576 ($\Delta cs_{t,p}$), it is calculated as a function of the difference of the current carbon
 1577 stock from the carbon equilibrium value of pasture p (ε_p) (in $\text{t}\cdot\text{ha}^{-1}$). The
 1578 parameter r represents the carbon losses by plant respiration and determines
 1579 the speed in which equilibrium is reached. For simplicity, **Eq. 62** can be
 1580 written as $\Delta cs_{t,p} = r(\varepsilon_p - \varphi_{t,p})LU_{t,p}$, where:

$$\varphi_{t,p} = cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} RPA_{t,p}$$

1581
 1582 (62b)

1583 **Eq. 62b** represents the carbon stocks in pasture p in year t just before carbon
 1584 sequestration occurs, i.e., the amount of carbon transferred to pasture p in
 1585 year t from pasture p in $t-1$ or other land uses.

1586

1587 **Eq. 63** and **64** are analogous to **Eq. 61** and **62**, respectively, but since for
 1588 $p=C$ there is area converted from natural vegetation (EDA_t+DA_t), the
 1589 carbon (assumed in equilibrium) from natural vegetation has to be
 1590 transferred to pasture C as well (fourth term in the RHS of **Eq. 63**), where σ
 1591 represents the soil organic carbon in equilibrium of natural vegetation ($\text{t}\cdot\text{ha}^{-1}$).
 1592 ¹).

1593

1594 **Eq. 65** accounts for the soil organic carbon under crops ($cs_{t,c}$). As crops
 1595 have to be planted every year, the stocked carbon is given by the transferred
 1596 carbon from the previous land use, plus the sequestration rate. Analogous to
 1597 the pasture sequestration rate, it is calculated as the difference between the

1598 current stock and equilibrium (ϵ_c), multiplied by the plant carbon respiratory
1599 losses.

1600

1601

1602 **Calculation of restoration and land use change costs**

1603

1604

1605 We assume the cost – and therefore inputs - necessary to change from X to Y ,
1606 where X and Y can be any element in $LU = \{A, B, C, D, E, F, \text{Corn}(\text{silage}),$
1607 $\text{Corn}(\text{grain}), \text{Soybeans}\}$ is given by:

1608

$$1609 \text{Cost}(X,Y) = \text{Cost}(F,Y) - \text{Cost}(F,X)$$

1610

1611 The $\text{Cost}(F,Y)$, and the description and amount of inputs, for any Y in LU is
1612 presented in Table S3-S7.

1613 In the case where $X = Y$, “the cost to restore from X to X ”, represents the
1614 cost of maintaining the DMP X , i.e., avoiding degradation. The amount of
1615 input and cost to keep any DMP level is described in Table S4.

1616 The inputs used for the pasture restoration and plantation of corn and
1617 soybeans followed recommendations in Sousa et al. (2004) and Tomé Junior
1618 (1997). Machinery and services were added following technical
1619 recommendations established by Agronomists (MSc. Paulo Roberto
1620 Albertini and Dr. Luis Gustavo Barioni, Personal Communication,
1621 Campinas, 2013) and by Veterinary (Dr. Tiago Zanett Albertini, Personal
1622 Communication, Campinas, 2013), with expertise in livestock and crop
1623 systems of production in the *Cerrado* biome. Further, item prices were
1624 based on time series collected from the Institute of Agricultural Economics
1625 (IEA, 2012) and were deflated to the 2012 value using IGP-DI (FGV, 2012).

1626

1627 **Model calibration**

1628

1629 This section describes the process used to obtain the pasture Average Dry
1630 Matter Productivity (ADMP) from 2006, as used in the construction of the
1631 baseline scenario (section 2.5). The land use changes dynamically as a
1632 function of time (composition of the total land across the pastures types and
1633 crops), as well as the herd dynamic (composition of animals age cohorts).
1634 However, after several years, the solution tends to reach equilibrium; i.e.,
1635 land and herd composition tends to present similar values throughout the
1636 simulation. To obtain the ADMP for 2006, we ran the model with the 2006
1637 pasture area and beef demand constant for 25 years of simulation. As the
1638 solution stabilized, we calculated the ADMP as a function of the
1639 composition of pasture types for the stabilized solution and the values of
1640 DMP in Table 1, obtaining the value of 10 t-DM.ha⁻¹.yr⁻¹.

1641

1642

1643 **References**

1644 FGV (Getulio Vargas Foundation), 2012. General Price Index - Internal
1645 Availability [WWW Document]. URL <http://portalibre.fgv.br/> (accessed
1646 3.26.15).

1647 IEA, 2012. Survey of monthly average prices received by farmers [WWW
1648 Document]. URL <http://www.iea.sp.gov.br/out/bancodedados.html> (accessed
1649 3.26.15).

1650 Sousa, D.M.G. de, Lobato, E., 2004. Cerrado: correção do solo e adubação,
1651 Planaltina: Embrapa Cerrados. Embrapa, Planaltina - DF.

1652 Tomé Junior, J.B., 1997. Manual para interpretação de análise de solo /
1653 Análise de solo. Livraria e Editora Agropecuária, Guaíba, RS, Brazil.

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