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## Assessing the full distribution of greenhouse gas emissions from crop, livestock and commercial forestry plantations in Brazil's Southern Amazon

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*This study focuses on evaluating the full distribution of greenhouse gas (GHG) emissions related to agricultural land-use change in Mato Grosso, Brazil, both from a farmer and policy perspective. By combining three simulation models as well as data from field experiments, we present a novel Integrated Assessment approach that evaluates a large set of production systems, management practices, technologies, climatic conditions, and soil types with very high spatial resolution. The main component of our application is a multi-agent mathematical programming simulator that links socio-economic and biophysical constraints at farm-level and, hence, simulates farmer decision-making and policy response. We estimate the GHG emissions related to the full range of farm production systems and sources, such as inputs, machinery production, diesel consumption, soil processes, land use change (soil organic carbon and carbon stock from vegetation) and enteric fermentation. The results of our simulations indicate that GHG emissions in Mato Grosso are very sensitive to alternative land use change scenarios. The largest source of GHG emissions from crop and eucalyptus production is the use of farming inputs, while for cattle production it is the emission from enteric fermentation. Final simulation results regarding farmer policy response will be presented at the ICAE conference.*

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**JEL Codes:** C63, Q01

#1027



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This study focuses on evaluating the full distribution of greenhouse gas (GHG) emissions related to agricultural land-use change in Mato Grosso, Brazil, both from a farmer and policy perspective. By combining three simulation models as well as data from field experiments, we present a novel Integrated Assessment approach that evaluates a large set of production systems, management practices, technologies, climatic conditions, and soil types with very high spatial resolution. The main component of our application is a multi-agent mathematical programming simulator that links socio-economic and biophysical constraints at farm-level and, hence, simulates farmer decision-making and policy response. We estimate the GHG emissions related to the full range of farm production systems and sources, such as inputs, machinery production, diesel consumption, soil processes, land use change (soil organic carbon and carbon stock from vegetation) and enteric fermentation. The results of our simulations indicate that GHG emissions in Mato Grosso are very sensitive to alternative land use change scenarios. The largest source of GHG emissions from crop and eucalyptus production is the use of farming inputs, while for cattle production it is the emission from enteric fermentation. Final simulation results regarding farmer policy response will be presented at the ICAE conference.

21

## 22 **1. Introduction**

23           In 2009, the federal government of Brazil pledged to reduce its greenhouse gas (GHG)  
24 emissions and implemented national policies to enforce it. Since a large share of Brazil’s emissions  
25 comes from agriculture (approx. 35%, according to MCTI (2016)), the government implemented  
26 the ABC Plan (low-carbon agriculture plan, in Portuguese, “Plano de Agricultura de Baixo  
27 Carbono”) in 2010, which consists of seven programs, six of them focusing on climate change  
28 mitigation technologies and one on climate change adaptation.

29           The agricultural sector is of great importance to the economic development of Brazil and  
30 accounts for approx. 40% of its exports (MAPA, 2017). The most important policy implemented  
31 by the Brazilian government within the ABC Plan is the ABC Credit Program, which supports the  
32 adoption of low-carbon agricultural practices by offering loans with subsidized credit for farmers.  
33 Reports from the ABC Observatory (an initiative aiming to engage society in the debate on low-  
34 carbon agriculture) argue, however, that the program has not yet achieved its full potential. During  
35 the last cropping season (2015/2016), the program only lent 68% of the total amount made  
36 available by the federal government (Observatório ABC, 2016). Furthermore, there is a lack of  
37 information on the program’s potential to reduce GHG emissions and on its adoption (Anonymous  
38 2017<sup>1</sup>; Gil et al., 2015).

39           Agricultural production systems in Brazil are usually cultivated as single crops in  
40 monoculture or as succession/rotation. With its ABC credit program, the Brazilian government  
41 promotes the use of integrated systems of crops, livestock, and forestry (herein, IAPS – integrated

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<sup>1</sup> Details omitted for double-blind reviewing.

42 agricultural production systems) as a strategy to reduce environmental impacts and reduce GHG  
43 emissions. By combining cropping, livestock and/or forestry activities in the same area (at the  
44 same time or in rotation), farmers are supposed to take advantage of the synergy effects, which  
45 might increase yields, reduce input use, enhance nutrient cycling, reduce plant disease and/or  
46 improve soil quality (Hendrickson et al., 2008a). The integration of production systems may allow  
47 farmers to diversify production and market risks, improve profitability and minimize  
48 environmental impacts (Hendrickson et al., 2008b; Hanson and Franzluebbers, 2008).

49         Despite the potential benefits of IAPS, the adoption of integrated systems by farmers in  
50 Mato Grosso is still slow. A recent survey of the Brazilian Agricultural Research Corporation  
51 (EMBRAPA, 2016) showed that IAPS is practiced on less than 5% of the total agricultural land in  
52 MT. Through computer simulation, Anonymous (2017) estimated a positive impact of the ABC  
53 credit on IAPS adoption, with an increased share of forest systems. From the farmer perspective,  
54 however, there are still difficulties and barriers to be overcome when adopting IAPS as revealed  
55 in Gil et al. (2015): (1) higher labor requirements; (2) lack of know-how and technical knowledge;  
56 (3) implementation costs and; (4) difficulties in commercializing forestry products.

57         From the government perspective, there have been efforts to offer subsidized credit to IAPS  
58 adoption, but the subsequent impacts on GHG emissions from agriculture are not yet clear. Recent  
59 literature on GHG emissions is increasing but there are only a few empirical studies applied to  
60 Mato Grosso. Cerri et al. (2016) evaluated the main sources of GHG emission in beef production  
61 systems for 22 farms in Mato Grosso, while Nogueira et al. (2015) evaluated nitrous oxide  
62 emissions in three beef production field experiments in the north of MT. A life cycle assessment  
63 (LCA) of soybean cultivation was carried out by Raucci et al. (2015) for 55 farms in MT, while  
64 Castanheira and Freire (2013) investigated a life cycle GHG balance of soybean produced in Latin

65 America through different scenarios of land use, cultivation, and transportation. All studies pointed  
66 to the crucial effect of land use change emissions, a variable not always taken into account in LCA  
67 (Cederberg et al., 2011). Moreover, LCA should capture more fully the heterogeneity of climate,  
68 soil type, and cultivation systems.

69 Therefore, we aim to contribute to the current literature by applying an agent-based  
70 bioeconomic simulation approach that enables us to evaluate a large variety of real-world  
71 agricultural production system at farm level. Additionally, we propose to evaluate, in a holistic  
72 manner, the respective GHG emissions of those systems and assess them together with farmer  
73 economic incentives and policy responses. The advantages of our agent-based bioeconomic  
74 modeling approach are: (1) consideration of a large set of agricultural production systems, crop  
75 management practices, and technologies; (2) consideration of farm heterogeneity in terms of assets  
76 and capital endowments; and (3) consideration of agroecological constraints (such as local weather  
77 and soil types).

78 We applied our modeling approach in the Brazilian state of Mato Grosso (MT), a major  
79 producer and exporter of agricultural commodities. Data from farm surveys, field experiments and  
80 life cycle databases were used for model parameterization and model validation. We evaluate GHG  
81 emissions from the existing large variety of agricultural practices in order to highlight remaining  
82 knowledge and data gaps and identify future research priorities. Simulation experiments are  
83 underway to evaluate the cost efficiency of ABC Integration credit and to identify conditions that  
84 might speed up the diffusion of low-carbon agricultural practices. These simulation results  
85 regarding farmer policy response will be presented at the ICAE conference in Vancouver.

## 86 **2. Data and Methods**

### 87 2.1. Study region and agricultural practices

88 The Federal State of Mato Grosso (MT) is located in west-central Brazil and covers an area as  
89 large as France and Germany taken together. MT is the main agricultural producer of soybean,  
90 maize, and cotton and has the country's largest cattle herd (CONAB, 2017). Ecologically, MT has  
91 three different ecosystems, the Amazon rainforest, the swampy Pantanal area, and the Cerrado  
92 "bushland" that comprises approximately 60% of the state's native forest area (IMEA, 2017).

93 Following the sampling procedure of IMEA (2010), our IA application was parameterized for  
94 five macro-regions in Mato Grosso: West, Mid-North, Southeast, South Central and Northeast  
95 with representative survey sites as shown in the appendix. Taken together, the five macro-regions  
96 together produce almost the entire agricultural output of Mato Grosso. The major crops produced  
97 are soybean, maize, and cotton - which are grown in a highly intensive double crop production  
98 system. Soybean is usually sown at the onset of the rainy season, while maize is sown in succession  
99 during the second season and harvested in the dry season. Cotton is usually cultivated after soybean  
100 or after a cover crop, such as millet or sorghum.

101 Farmers can choose between multiple sowing dates, nitrogen amounts, seed maturity groups -  
102 herein MG - and, seed varieties (for example, farmers in different regions employ different types  
103 of pesticides and choose different intensity of machinery use, etc.). Crops with longer maturity  
104 cycles require more fungicide and insecticide applications; seed varieties require different  
105 pesticides (active ingredients), pesticide applications and quantities. A crop calendar with weekly  
106 resolution was created to capture the timing of agricultural activities at each survey site of IMEA.  
107 Detailed production technology analysis revealed more than 200 agricultural production activities



108 that are combined with specific soil fertility constraints for each macro-region of IMEA, resulting  
 109 in about 2000 crop-mix options at farm level. The complexity of farmer decision making increases  
 110 even further as favorable climate conditions now allow for a double cropping system, resulting in  
 111 40 feasible double crop combinations.

112 Cattle production systems in MT are based on large-scale extensive grazing systems and either  
 113 focus on cattle fattening and beef production or on cattle breeding. We identified about 20 cattle  
 114 production systems with different intensity levels (extensive, semi-intensive or intensive),  
 115 production cycles (breeding, fattening or full cycle) and grazing inputs (*brachiaria brizantha* or  
 116 unmanaged native grassland).

117 Moreover, we specified three types of forestry production systems with eucalyptus (*eucalyptus*  
 118 *urograndis*), according to production cycle and final product. The first eucalyptus system focuses  
 119 on producing firewood with a 7-year production cycle, the second one has a 12-year production  
 120 cycle and produces both firewood and wood, and the third one only produces wood and has a 14-  
 121 years production cycle.



122

123

Fig. 1 Overview of agricultural practices in Mato Grosso

124

### 125 2.1.1. Typical production systems observed in Mato Grosso

126 Costs and benefits of local production systems were identified for the study region according  
127 to the IMEA agricultural production cost survey (IMEA, 2013), the planted forests report of Mato  
128 Grosso (FAMATO, 2013), Mato Grosso's cattle ranching report (IMEA, 2016) and with local  
129 experts. Typical agricultural practices for soybean, maize and cotton production at the site of  
130 Sorriso (Mid-North), for example, are, respectively: sowing dates (01/Oct, 06/Feb and 15/Jan),  
131 nitrogen amount (0 kg/ha, 80kg/ha and 185 kg/ha), varieties (Herbicide Tolerant, Insect Resistant  
132 and Insect Resistant) and soybean maturity group (MG VIII for crop rotations with maize and MG  
133 VII for crop rotations with cotton).

134 Typical cattle practices focus on a full cycle system, which takes into account two production  
135 systems, breeding and fattening, both extensive systems with the following characteristics,  
136 respectively: stocking rates (0.83 and 1.0 animal unit per hectare, respectively), pregnancy rate  
137 (72%), slaughter age (36 months), carcass yields (51%) and slaughter weight (555 kg). Typical  
138 forestry production system focuses on firewood production in a seven years' cycle.

### 139 2.2. Software used

140 In order to evaluate a wide range of agricultural production systems in full detail at farm  
141 production level, we applied an integrated assessment (IA) approach that simulates farm-level  
142 decision making under consideration of resource availability, agroecological constraints and GHG  
143 emissions. As depicted in Fig. 2, our IA approach integrates three software packages, MPMAS  
144 (Mathematical Programming-based Multi-Agent Systems), MONICA (Model for Nitrogen and  
145 Carbon in Agro-ecosystems) and CANDY (Carbon and Nitrogen Dynamics).

146 We advance the modeling approach published in Anonymous (2017) by incorporating life-  
 147 cycle GHG balances in our simulations. Since a detailed explanation of model parameterization  
 148 and model validation is already available in Anonymous (2017), this section gives a quick  
 149 overview of our software system only and then focuses on providing a detailed description of  
 150 model improvements, especially the implementation of GHG balances.

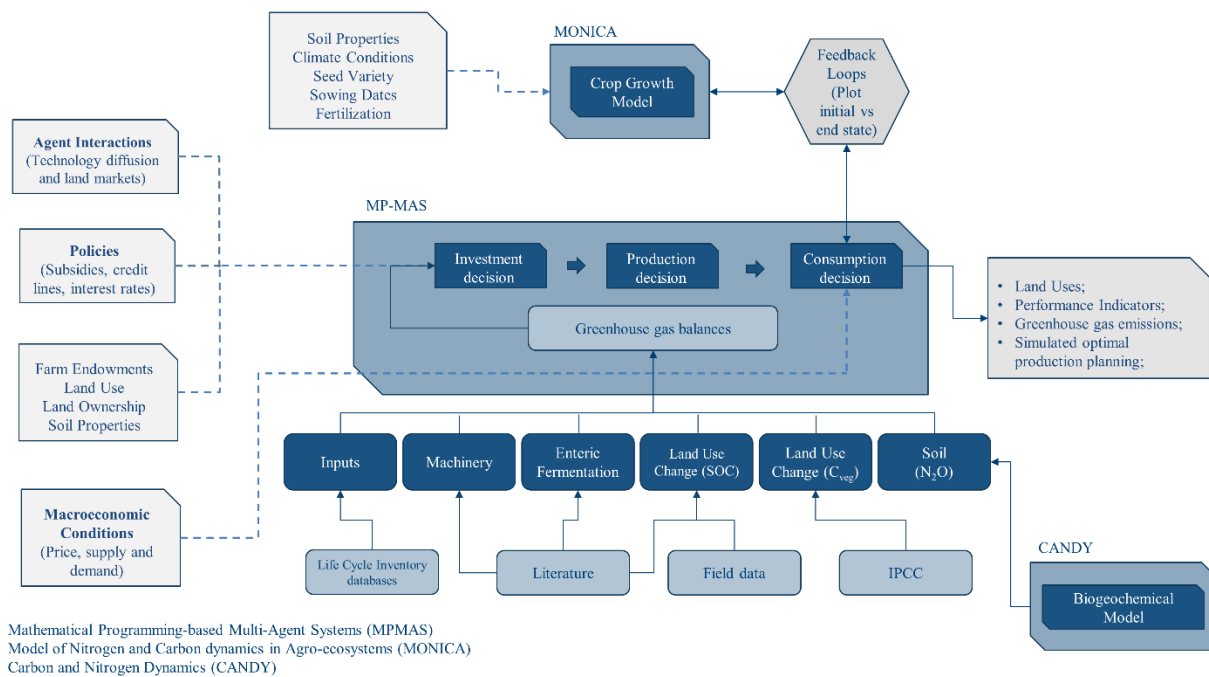


Fig. 2 Model flow chart and data sources

153 The main component of our IA application is the agent-based software package MPMAS  
 154 which simulates farm-level decisions related to investment (i.e. which machinery to buy),  
 155 production (i.e. which crops to grow) and consumption (i.e. how much to sell, withdraw or save  
 156 for future periods) using Mixed Integer Linear Programming (MILP). For this current application,  
 157 a statistically consistent agent population was created for the study region as described in  
 158 Anonymous (2017). 844 farm agents maximize expected farm income recursively by solving 3  
 159 annual decision problems (investment, production, and consumption) over each period. Each

160 agent's MILP consisted of 4,030 decision variables (162 integers) and 4,012 constraints. More  
161 details, such as software descriptions, model features, and ODD protocol can be found in  
162 Schreinemachers and Berger (2011).

163 The second component of our IA application is the MONICA software, which was used to  
164 estimate crop yield responses of different cultivars, nitrogen fertilization rates, soil types, and  
165 climatic conditions. By integrating MPMAS and MONICA, technical and environmental  
166 constraints can be incorporated into our mathematical programming approach and, thus, allows us  
167 to assess farmer decision-making and policy response subject to specific local environmental  
168 conditions. At the investment and production stages, agents in MPMAS decide whether to invest  
169 and produce based on expected local yields and prices. At the consumption stage (during harvest),  
170 agents update their decisions based on actual crop yields on their plots – simulated by MONICA  
171 – and crop prices received for a given year. Further model details and software specifications are  
172 described in Nendel et al. (2011). In total, for all 14 simulated years (from 2000 to 2013), 420 crop  
173 yields were simulated for soybean, 6,300 for maize and 10,780 for cotton.

174 The third software component is CANDY, a simulation model providing N<sub>2</sub>O fluxes resulting  
175 from crop-soil management practices and subsequent effects on underlying biophysical processes,  
176 such as soil moisture. N<sub>2</sub>O-N fluxes were simulated using an extended version of the CANDY  
177 model, which provides information about carbon (C) stocks in soil, organic matter turnover,  
178 nitrogen (N) uptake by crops, leaching, and water quality (Franko et al., 1995). This model has  
179 originally been developed in order to describe carbon turnover in agriculturally used soils under  
180 temperate conditions. Recently, the model has been used to reproduce observed N<sub>2</sub>O-N fluxes  
181 from soils under Brazilian cattle pastures (Meurer et al., 2016) and cropland under soybean.  
182 Gaseous N losses are assumed to result from denitrification, which is regulated by soil moisture

183 and soil temperature. The amount of emissions is a function of the size of the NO<sub>3</sub>- pool, the  
184 amount of C in the active organic matter, and a denitrification factor. Since information about the  
185 initial soil carbon conditions at the various survey sites was lacking, we assumed the soil organic  
186 carbon to be in steady state according to the individual scenario. Thus, no changes of the soil  
187 carbon stocks (and resulting CO<sub>2</sub> fluxes) were included in our current simulations.

188 Based on the crop management decisions in MPMAS and the resultant crop yields simulated  
189 by MONICA, CANDY simulates daily nitrous oxide (N<sub>2</sub>O) fluxes by taking into consideration all  
190 production systems at farm level, with specific crop rotation schemes, sowing dates, harvesting  
191 date, crop management practices, nitrogen application, stocking rates (exclusively for cattle  
192 systems) and local agroecological constraints (such as soil characteristics and weather conditions).  
193 In total, 27,170 annual GHG emission balances were simulated for 2,090 agent production  
194 decisions (combination of crop rotation practices and region-specific variables) over 14 years.

### 195 2.3. Specific LCA Data

196 Based on the approach proposed by Castanheira and Freire (2013), we established a life cycle  
197 GHG inventory for agricultural production systems for farms in MT. The system boundary was  
198 "cradle to gate" and GHG emission factors were estimated for inputs (fertilizers, pesticides, and  
199 others), machinery production, diesel consumption, soil processes (N<sub>2</sub>O), land use change  
200 (annualized change of soil organic carbon - SOC - and carbon stock from vegetation - C<sub>VEG</sub>) and  
201 enteric fermentation (for cattle activities). All GHG were estimated as equivalents of carbon  
202 dioxide (CO<sub>2</sub>e) using the global warming potential (GWP) conversion factors of each gas provided  
203 by the Intergovernmental Panel on Climate Change (IPCC) (Myhre et al., 2013).

204 Emission factors from fertilizers, pesticides, and other inputs (i.e. soil amendments, seeds,  
 205 adjuvants, animal feed) are retrieved from the carbon footprint tool CCaLC V2.0 (Azapagic, 2017)  
 206 and the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model -  
 207 GREET Model - database (Argonne National Laboratory, 2015) and account for the carbon  
 208 footprints from “cradle to gate”. Emissions from machinery production are calculated according  
 209 to Rotz et al. (2010) and take into consideration machinery mass and are amortized by lifetime,  
 210 according to the following equation:

$$211 \quad CO_2e_{mach} = \frac{Mass}{lifetime} \times EmissionFactor_{mach}$$

212 where  $CO_2e_{mach}$  is the production emission of the machinery (in kg of  $CO_2$   $h^{-1}$ ), Mass is the  
 213 machinery mass in kg, lifetime is the machinery lifetime in hours and  $EmissionFactor_{mach}$  is the  
 214 machinery emission factor (in  $CO_2e$   $kg^{-1}$ ) estimated by Rotz et al. (2010). Machinery lifetime and  
 215 diesel consumption are measured by the Brazilian National Supply Company (CONAB, 2010).  
 216 Emissions due to diesel combustion are calculated as follows:

$$217 \quad CO_2e_{mach} = \frac{Mass}{lifetime} \times EmissionFactor_{mach}$$

218 where  $CO_2e_{diesel}$  is the diesel emission factor per hour of machinery use (in kg  $CO_2$   $h^{-1}$ ); HP  
 219 the machinery horsepower; DC is the diesel consumption factor;  $EF_{d,C}$  is the emission factor for  
 220 diesel combustion (in kg  $CO_2e$   $kg^{-1}$ );  $EF_{d,P}$  is the emission factor due to diesel production (in kg  
 221  $CO_2e$   $kg^{-1}$ ) and  $\delta_{diesel}$  is the diesel density (in kg  $L^{-1}$ ).

222  $N_2O$  emissions from soil microbiological processes for crop and cattle production are estimated  
 223 with CANDY based on local crop management practices, fertilization amounts, soil characteristics  
 224 and daily weather data. Emissions are estimated on a daily basis and cumulated for each crop,

225 season, agricultural practice and region and then converted to carbon dioxide equivalent (CO<sub>2e</sub>)  
226 using 298 as global warming potential factor (Myhre et al., 2013) N<sub>2</sub>O emissions are simulated  
227 over a 14-year period (from 2000 to 2013) and the system was assumed to be in a steady-state. In  
228 order to avoid overestimation of N<sub>2</sub>O emissions, the first five years of simulation have been  
229 excluded from our analysis.

230 N<sub>2</sub>O emissions from urine and fecal deposition during grazing were also taken into  
231 consideration by CANDY. The biomass N pool is reduced due to grazing, which is influenced by  
232 the stocking rate and animal age. The CANDY model treats animal faeces as organic amendments  
233 that will influence soil organic matter and N<sub>2</sub>O producing processes. Methane emissions from  
234 animal waste deposited on the field during grazing were not taken into account since, as pointed  
235 out by Cerri et al. (2016), a minimum quantity of CH<sub>4</sub> emission is expected from this source.

236 Forestry plantation N<sub>2</sub>O emissions are estimated from an EMBRAPA (Brazilian Agricultural  
237 Research Corporation) field experiment located in Sinop, MT (Rodrigues et al., 2015) with an  
238 *eucalyptus* plantation under monoculture system. The hybrid *eucalyptus urograndhis* (H13) was  
239 planted in 2011 in an arrangement of 3,0 m x 3,5 m (952 trees ha<sup>-1</sup>). Nitrous oxide samples were  
240 taken once a week, from November 2013 to October 2014 with the closed static chamber-based  
241 technique, in which change in gas concentration - determined by a gas chromatography - over time  
242 is used to calculate flux.

243 Carbon losses due to land use change (LUC) were estimated following European Commission  
244 (2010) guidelines by subtracting actual land use (which is simulated by MPMAS) from the initial  
245 C stocks. We considered four land use types: cropland, degraded pasture, managed pasture and  
246 forest plantation. CVEG stocks are taken from European Commission (2010); SOC stocks of  
247 cropland, degraded and managed pasture are estimated from field experiments (Strey et al., 2016);

248 and SOC stocks of forest plantations are estimated with normal average from three literature  
249 sources (Inácio, 2009; Pulrolnik et al., 2009; Rangel and Silva, 2007). The difference in C stocks  
250 is amortized for 20 years, as recommended by Flynn et al. (2012), and converted to kilograms of  
251 CO<sub>2</sub>e per year and hectare according to the following formula:

$$252 \quad CO_{2eLUC}(R, LU) = (C_{initial_R} - C_{actual_{LU}}) \times \frac{M(CO_2)}{M(C)} \times \frac{1}{Period}$$

253 where CO<sub>2eLUC</sub> is the annualized GHG emission from changes in CVEG and SOC stocks due  
254 to LUC for each MT region (R) estimated in kilograms of CO<sub>2</sub>e per hectare and year; C<sub>initial<sub>R</sub></sub> is  
255 the initial SOC and CVEG stock for each MT macro-region (R); C<sub>actual<sub>LU</sub></sub> is the actual SOC and  
256 CVEG stocks for each simulated land use (LU); M(CO<sub>2</sub>) is the molecular mass of CO<sub>2</sub> (44 g mol<sup>-1</sup>);  
257 M(C) is the atomic mass of carbon (12 g mol<sup>-1</sup>); and *Period* is the amortization period. Since in  
258 our current modeling setup farm agents are not allowed to clear their native forest land and their  
259 decision-making process refers to existing cropland only, initial C stocks are estimated based on  
260 cropland use.

261 Emissions from enteric fermentation are calculated according to the IPCC guidelines (IPCC,  
262 2006), based on data from the *Second Brazilian Inventory of Anthropogenic Greenhouse Gas*  
263 *Emission* for methane emission factors under MT conditions (Lima et al., 2010) and weighted  
264 accordingly to each production system (animal category and sex). Emissions from enteric  
265 fermentation are estimated in kilogram of carcass by dividing it by live weight gain (in kg of live  
266 weight gain) - estimated with values taken from ANUALPEC (2013) - and multiplying it to carcass  
267 yield (which is estimated by local experts and depends on production system and intensity). All  
268 coefficients are then weighted by their cattle stocking rate (with three intensity levels: extensive,  
269 semi-intensive and intensive) and used to calculate carbon stocks for cattle production systems of



270 agents simulated by MPMAS. Calculation of CO<sub>2e</sub> is done by applying the 34 global warming  
271 potential for Methane (Myhre et al., 2013).

272 Given the current lack of available data on SOC stocks for different production systems and  
273 management practices, we assumed that degraded pasture land use represents all production  
274 systems without fertilizer application (i.e. extensive production systems), while managed pasture  
275 land uses refer to production systems with fertilizer application (i.e. semi-intensive and intensive  
276 systems). SOC stocks for *eucalyptus* plantation were taken from field experiments on Minas Gerais  
277 state since there was no available data for Mato Grosso. Our model experiment takes into  
278 consideration six different soil types, but data on SOC stocks and soil emissions for *eucalyptus*  
279 were only available for one (*ferralsol typic*).

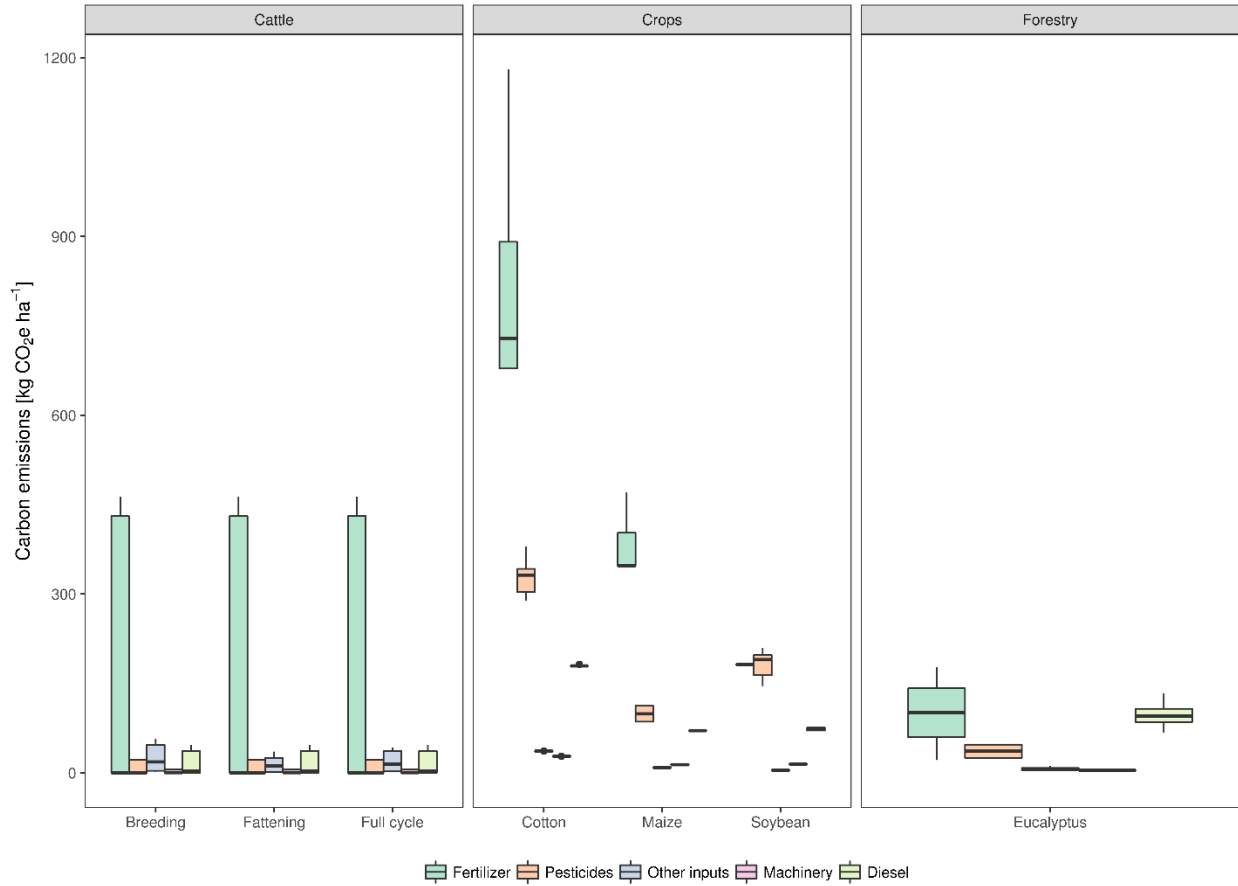
280 Our CVEG stocks stem from IPCC estimations that average over all management practices  
281 and climatic conditions taken into consideration in our IA approach. Emission factors for  
282 agricultural inputs were taken from LCA databases available online. However, these estimations  
283 are usually made for European countries which might also differ for Brazilian conditions, e.g.  
284 different energy mixes and transport emissions.

### 285 **3. Simulation Results**

286 In this section, we present preliminary results of our Integrated Assessment approach (final  
287 results will be shown at the ICAE in Vancouver). Subsections 3.1 to 3.4 present farm-level GHG  
288 balances for each source, subsection 3.5 presents the simulated carbon footprints for typical  
289 production systems in MT, and subsection 3.6 summarizes our findings with an analysis of the  
290 estimated GHG balances for all combinations of region-specific agricultural practices.

### 291 3.1. Input and machinery emissions

292 Fig. 3 depicts the simulated GHG emissions from inputs and machinery for agricultural  
293 practices in MT. Emissions are divided in five sources: fertilizers, pesticides, other inputs (such as  
294 seeds and animal food), machinery production and diesel combustion. The left pane shows the per-  
295 hectare input emissions for cattle production; the middle pane shows the per-hectare input  
296 emissions for crops and the right pane shows the per-hectare input emissions for forestry systems.  
297 The most significant source of input-related emissions is fertilizer (except for soybean, which does  
298 not receive any N fertilization). Emissions from pesticide application play an important role in  
299 crop production, while emissions from other inputs (mostly animal feed) and diesel have a  
300 significant impact in cattle production. Since soybean does not require any nitrogen application, it  
301 presents the lowest input-related emissions when compared with maize and cotton. GHG emissions  
302 are largest in cotton production due to high fertilizer and pesticide application rates.



303

304

Fig. 3 Simulated GHG emissions for agricultural practices in Mato Grosso (Box plots)

305

### 306 3.2. Enteric emissions

307 Cattle emissions are simulated for different intensity levels, which are determined by specific

308 coefficients, such as stocking rate (in animal units per hectare), pregnancy rate and grassland

309 management (such as the use of fertilizers and pesticides for soil maintenance and correction).

310 Emissions from enteric fermentation are shown in Fig. 4 for different production systems,

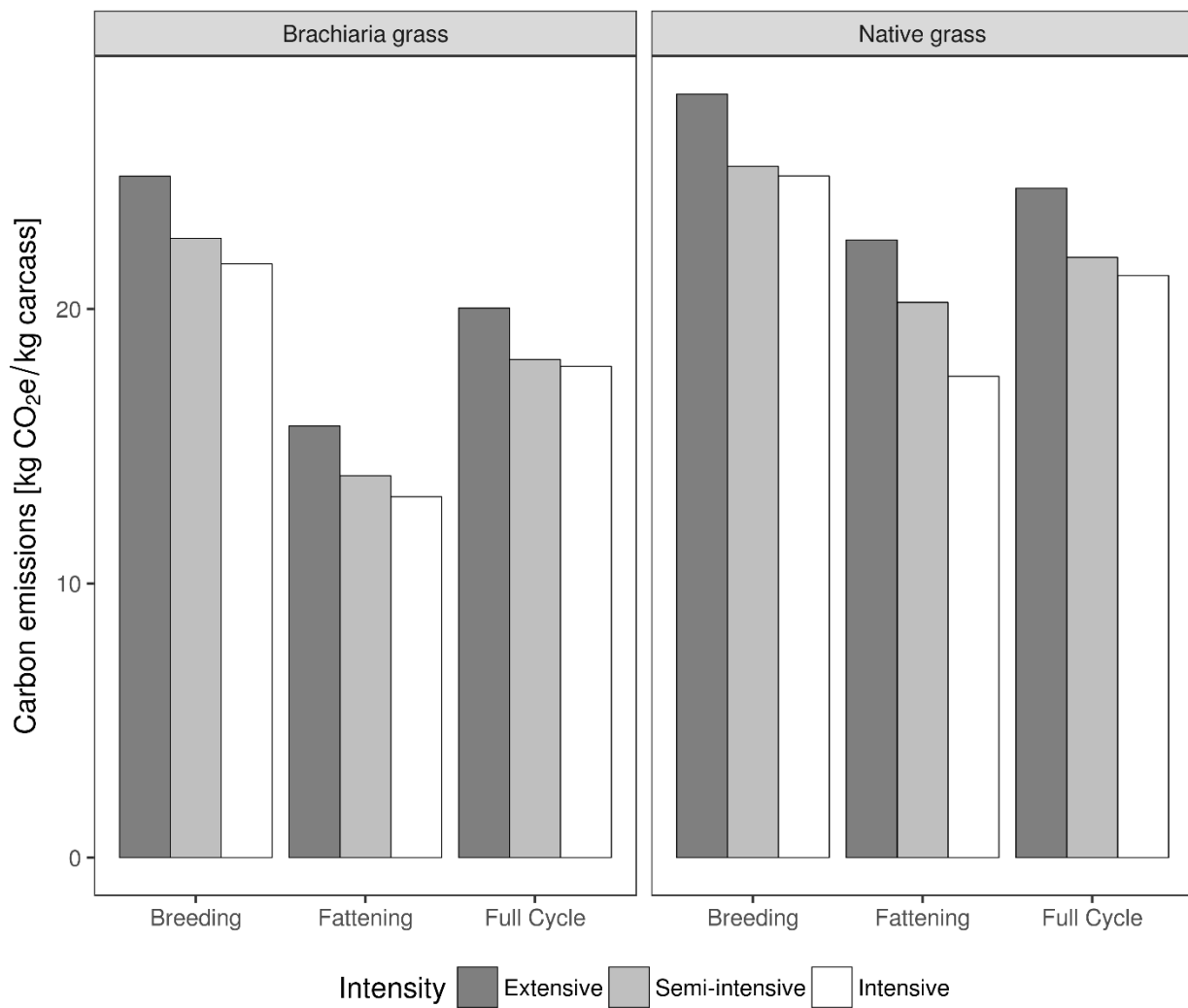
311 intensities, and types of grassland. Emissions per kilogram of carcass from native grasslands are

312 higher than from *brachiaria* grasslands since they have reduced yield rates due to lower forage

313 production. The intensification process increases the absolute emission stocks but reduces the

314 relative emission (emissions per kilogram of carcass) due to the reduction of the system's lifetime  
 315 and the increase in the animal live weight gain. The main factors affecting enteric fermentation  
 316 emissions are animal age and sex. Therefore, enteric emissions from extensive breeding systems  
 317 are higher due to the higher share of cows while fattening system emissions are lower due to their  
 318 higher share of young animals (mainly young bulls).

319



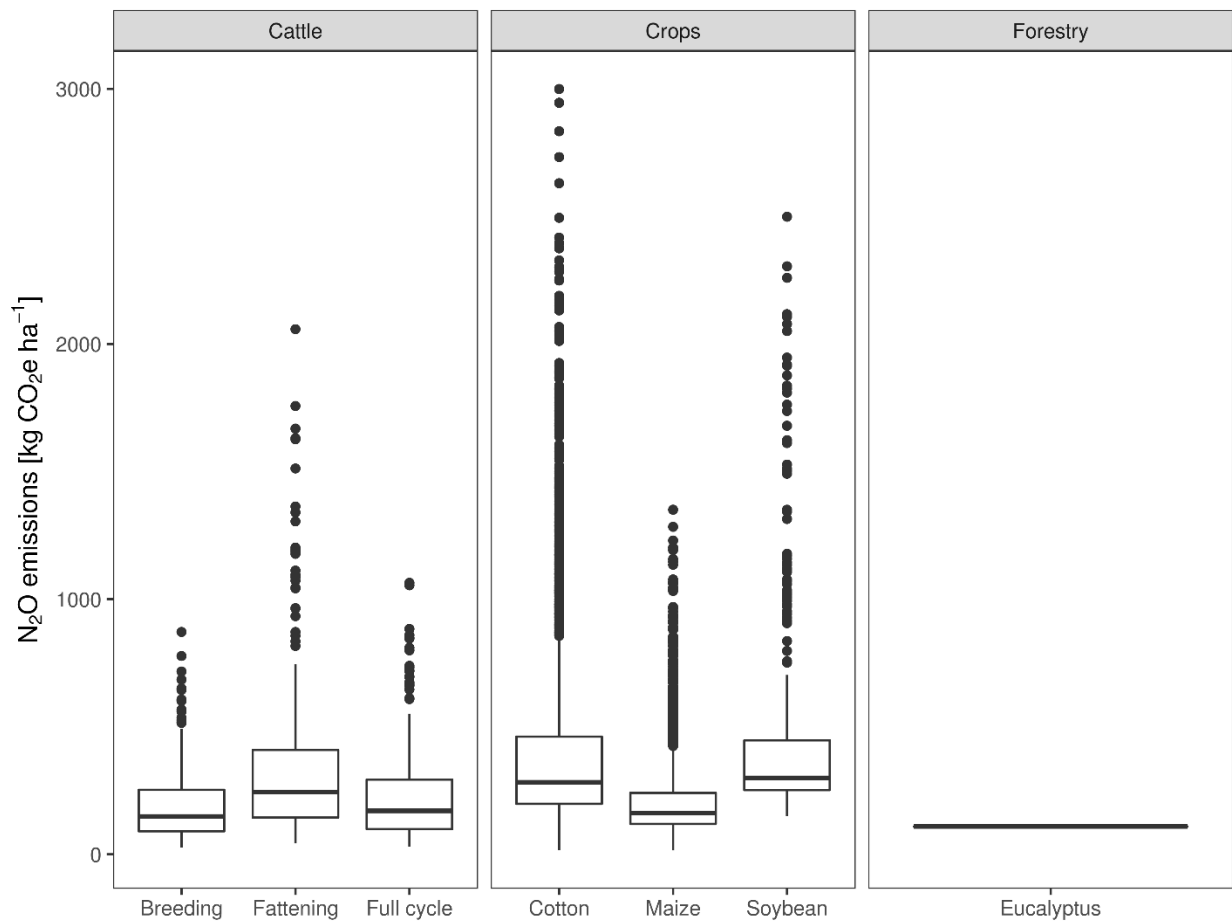
320

321

Fig. 4 Simulated GHG emissions of enteric fermentation for cattle production systems

322 3.3. Soil emissions

323 Fig. 4 depicts simulated values of nitrous oxide emissions estimated by CANDY and from  
324 field experiments over different agricultural practices in MT. Soil emissions from soybean and  
325 cotton are, on average, higher than maize due to the high use of fertilizers on those crop rotations.  
326 Variables which mostly influence N<sub>2</sub>O emissions are soil type (higher emissions from loamy,  
327 clayey soils) and the applied nitrogen amount (high emissions with higher nitrogen rate amounts).



328

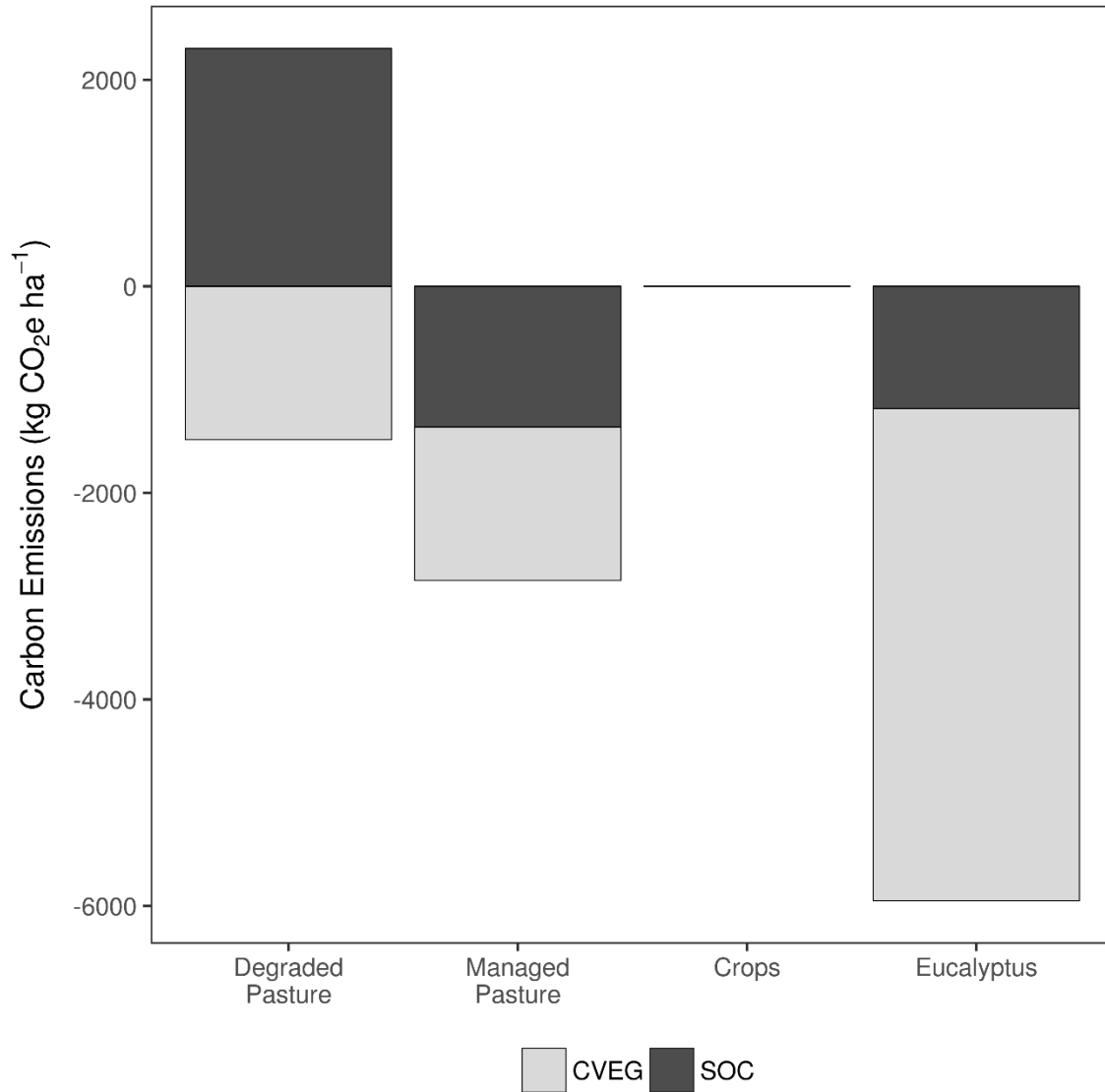
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Fig. 5 Simulated soil nitrous oxide emissions (Box plots)

331 3.4.Land use change emissions

332 Fig. 6 depicts the simulated carbon emissions (in kilograms of carbon dioxide equivalent per  
333 hectare) related to changes in SOC and CVEG (summing up to Land Use Change – LUC). LUC  
334 emissions from cropland are zero, since agents in our modeling approach take decisions based on  
335 current cropland area and thus cropland constitutes the emissions baseline. Degraded pasture  
336 showed highly positive LUC emissions, while commercial eucalyptus plantations imply highly  
337 negative emissions. In addition, the intensification of cattle production (“managed pasture”)  
338 showed a considerable reduction of emissions when compared to degraded pasture land use (which  
339 consists of extensive grazing in native grassland).



340

341 Fig. 6 Simulated GHG emissions related to changes in soil organic carbon (SOC) and carbon stock from vegetation (CVEG).  
 342 Reference point: Cropland land use

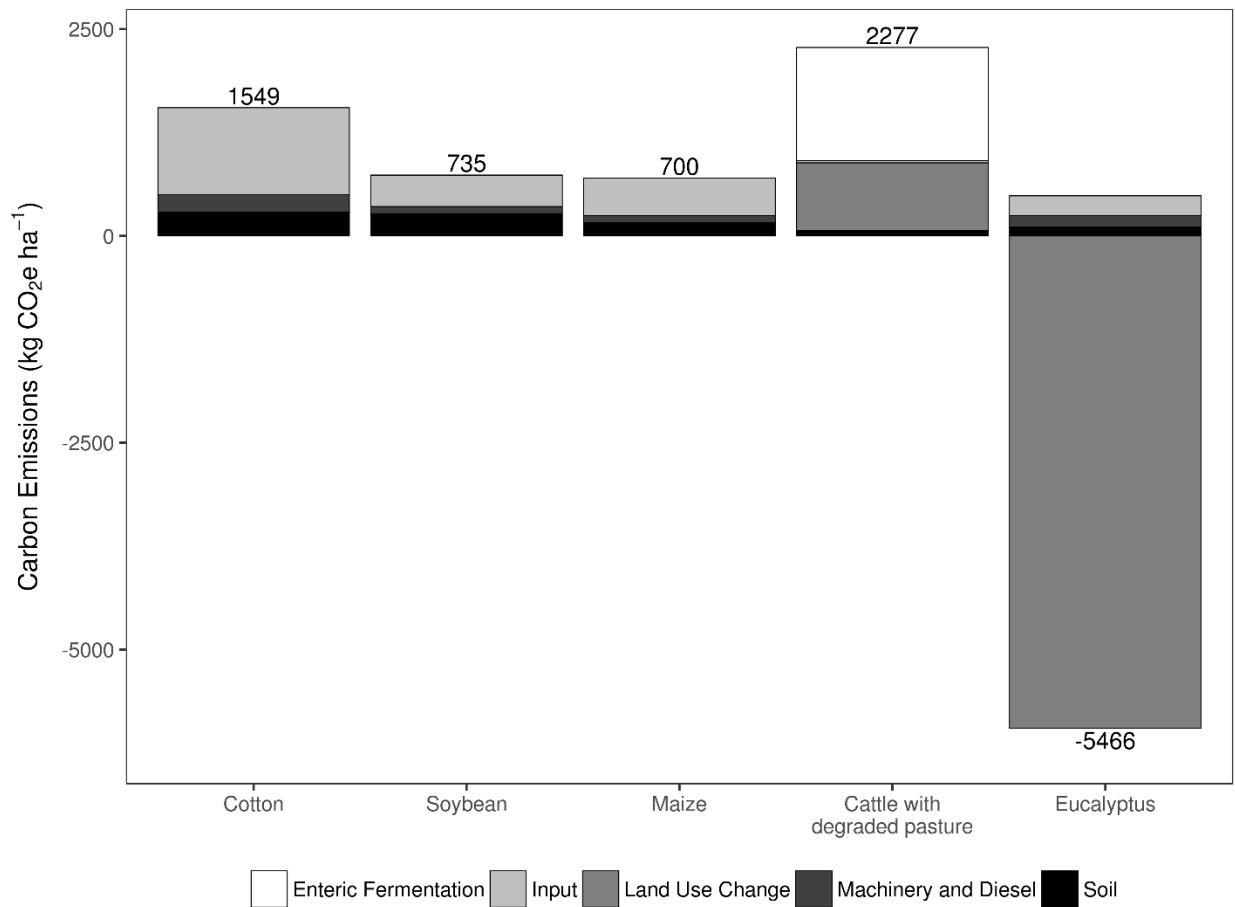
343

### 344 3.5. Carbon footprint for typical production practices in Mato Grosso

345 Fig. 6 summarizes the simulated total GHG emissions from typical agricultural practices (see  
 346 above in section 2.1.1) for different sources: enteric fermentation, production inputs, land use  
 347 change (SOC plus CVEG), machinery and fuel, and soil. Emissions are estimated in kilograms of

348 CO<sub>2</sub>e per hectare and year. Forestry production in our simulations showed the lowest values due  
 349 to their high share of carbon sequestration from land use change. Cropping systems presented only  
 350 positive GHG emissions since there is no negative effect of land use conversion for these systems.  
 351 Among cropping systems, cotton production showed the highest emissions due to its high input  
 352 use. Extensive cattle production systems (“degraded pasture”) showed the highest net emissions  
 353 due to enteric fermentation and land use change emissions.

354



355

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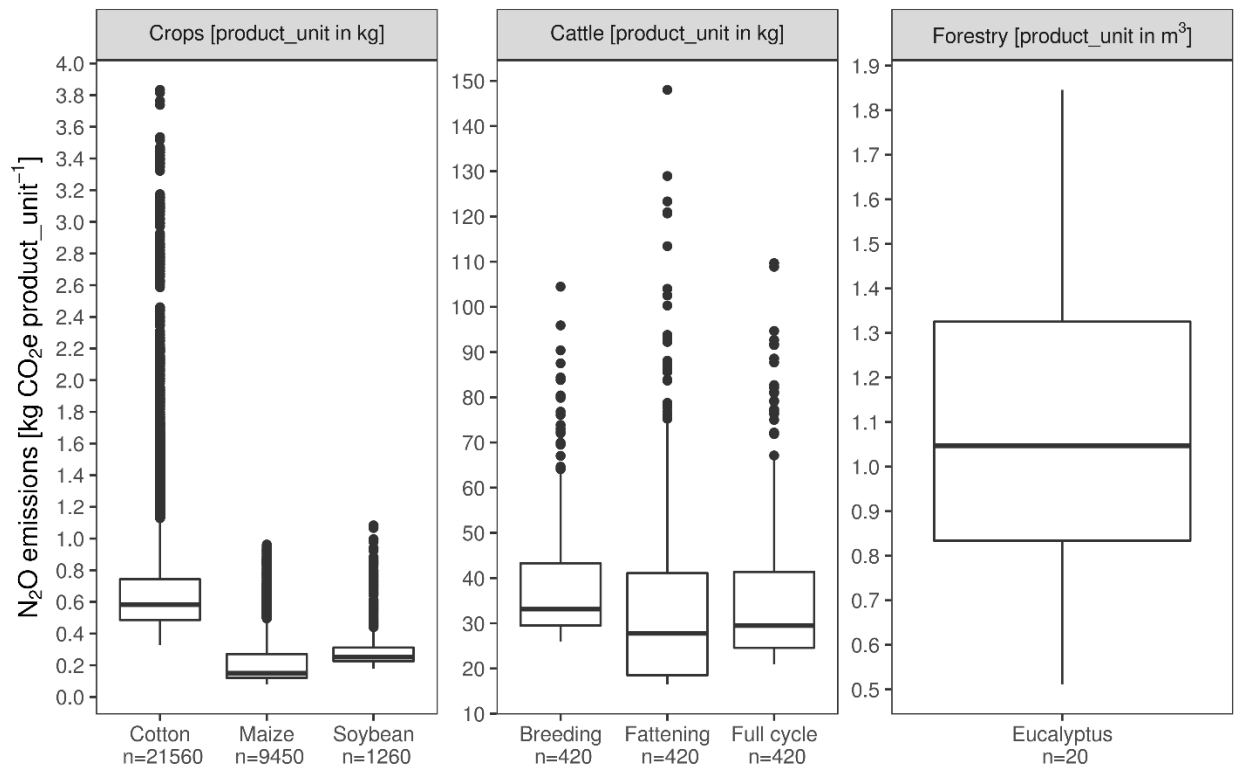
Fig. 7 Simulated total GHG emissions for typical production systems in Mato Grosso

357



358 3.6. Primary GHG emissions for production practices in Mato Grosso

359 Fig. 8 presents the simulated GHG balances for the full range of production systems in Mato  
 360 Grosso. Primary emissions are calculated by summing all sources of emissions except land use  
 361 change, such as emissions from agricultural inputs, enteric fermentation, machinery production,  
 362 diesel combustion, and soil. Large variation can be observed for most of the production systems.  
 363 The large variation of GHG emissions in cattle production are due to the heterogeneity of intensity  
 364 levels (i.e. extensive, semi-intensive and intensity), which influences key variables such as  
 365 fertilizer application, system lifetime, pregnancy rate, etc. Emissions from cotton are significantly  
 366 higher than soybean and maize due to the high use of inputs and machinery.



367

368 Fig. 8 Simulated GHG emissions in carbon dioxide equivalents per product unit for different production systems (n = number of  
 369 observations).

## 370 **4. Discussion**

371 To the best of our knowledge, this study represents the first Integrated Assessment approach  
372 in Mato Grosso capable of evaluating agricultural carbon footprints in a holistic way at farm  
373 population level. Our median GHG emissions of soybean production lies above the one estimated  
374 by Raucci et al. (2015), but agrees in identifying crop inputs (fertilizer and pesticides) as the main  
375 source of GHG emissions, followed by soil, and machinery and fuel. The GHG emissions for  
376 maize and cotton production systems estimated by Torres et al. (2015) for hypothetical farm  
377 enterprise combinations in the southeastern United States are within our range of simulated  
378 emissions but higher than our interquartile range. This underlines the importance of farm-level  
379 simulation that is capable of capturing the heterogeneity of individual farm holdings together with  
380 their specific agroecological constraints. We therefore agree with Raucci et al. (2015), who admit  
381 that the majority of LCA studies in Brazil employ crop management data based on national  
382 averages or public databases which often do not represent the reality of a region.

383 Our GHG emissions from primary production (not including emissions from LUC) for a typical  
384 (=median) cattle production system were estimated at approximately 21 kg CO<sub>2</sub>e per kg of CW  
385 (carcass weight), which is lower than the national average value of 28 kg CO<sub>2</sub>e per kg of CW  
386 estimated by Cederberg et al. (2009). This underlines the importance of evaluating GHG emissions  
387 over the full range of agricultural practices, where the median represents a skewed distribution  
388 better than the arithmetic mean. Cerri et al. (2016) and Cederberg et al. (2009) indicate that the  
389 largest source of GHG emissions in beef production comes directly from the animal feeding. Fig.  
390 7 confirms this by displaying enteric fermentation as the main source of emission in cattle  
391 production (after land use change) – an emission source not considered by most other empirical

392 studies. As an example, Cederberg et al. (2011) argue that the omission of land use change  
393 emissions can lead to serious underestimates, especially for meat production.

394 In terms of land use change emissions, the results of our simulation suggest on the one hand  
395 that cattle production with managed pastures leads to net carbon sequestration due to the  
396 accumulation of soil organic carbon, which agrees with the study of Braz et al. (2013). Fertilized  
397 managed pastures adds litter and aboveground biomass, which contributes organic matter to the  
398 soil. On the other hand, cattle production with degraded pastures depletes the soil organic matter  
399 on tropical soils (Fonte et al., 2014).

400 Eucalyptus plantations have been shown to tendentiously increase SOC stocks in Brazilian  
401 soils, when previous land use was savanna or grassland, while a decrease takes place when  
402 rainforest was the preceding land use (Fialho and Zinn, 2014). Our results show a carbon net  
403 sequestration for SOC when land use changes from croplands to eucalyptus plantations, which is  
404 in accordance to findings of Rangel and Silva (2007).

405 Our simulations do not (yet) account for synergy effects of integrated production systems.  
406 From the farmer perspective, there is still a high degree of uncertainty regarding access to  
407 information and knowledge for IAPS occurrence (Gil et al., 2016). From the research point of  
408 view, Garrett et al. (2017) states that the currently available baseline empirical data is critical to  
409 increase the sophistication and multi-disciplinarity of modeling efforts related to IAPS. We expect  
410 to tackle some of these limitations by extending our modeling efforts with an uncertainty analysis  
411 similar to the one of Troost and Berger (2015), which could provide important information  
412 regarding potential synergy effects and its impact on land use and IAPS adoption.

413 It is important to point out that our findings reported here are based on preliminary simulation  
414 experiments, which are subject to data availability and quality constraints: One limitation at the  
415 modeling stage was that robust data was no (yet) available to parameterize all production activities,  
416 management practices and agronomic conditions. Instead, assumptions were made to fill those  
417 data gaps. Therefore, one must take those assumptions into consideration when evaluating our  
418 results.

## 419 **5. Conclusions**

420 This article presents an innovative approach for evaluating GHG emissions from crop,  
421 livestock and commercial forestry plantations, focusing on the implications of different production  
422 systems and agro-climatic conditions. For this reason, we applied a novel Integrated Assessment  
423 approach to simulate GHG balances in a globally important hot-spot of agricultural production and  
424 biodiversity. It combines the agent-based simulation package MPMAS, the process-based agro-  
425 ecosystem simulation model MONICA, the process-oriented biogeochemical model CANDY, as  
426 well as data from field experiments and literature to simulate carbon footprints of the full  
427 distribution of agricultural production systems taken into consideration the heterogeneity of soils,  
428 climatic conditions, crop management, and farming technologies.

429 In terms of carbon footprint, the preliminary results of our simulations indicate that the GHG  
430 balance at farm level is highly dependent on the proceeding land use of plots. The largest source  
431 of GHG for crops is the use of farm inputs; Emissions from enteric fermentation play the most  
432 important role in cattle production.

433 The amplitude of our simulated carbon footprints suggests that GHG emissions are sensitive  
434 to several social and environmental variables/constraints which are (so far) difficult to represent

435 in current LCA studies. This result underlines the importance of novel approaches that are capable  
 436 to capture those variables and constraints and their impact on farmers decision-making.

## 437 **Appendix**

438 Survey sites, soil types and climate characteristics. MAP = mean annual precipitation, MAT =  
 439 mean annual temperature.

Site No.	Macro-region	Survey Site	Soil type [WRB]	MAP [mm]	MAT [°C]
1	West	Sapezal	Ferralsol Dystrophic	1833	26
2	Mid-North	Sorriso	Ferralsol Dystrophic	2234	27
3	Southeast	Campo Verde	Ferralsol Dystrophic	1872	26
4	Southeast	Campo Verde	Cambisol Typic	1872	26
5	South Central	Tangará da Serra	Arenosol Dystrophic	2111	27
6	South Central	Tangará da Serra	Acrisol Dystrophic	2111	27
7	South Central	Tangará da Serra	Ferralsol Dystrophic	2111	27
8	South Central	Tangará da Serra	Ferralsol Typic	2111	27
9	Northeast	Canarana	Plinthosol Dystrophic	1960	27
10	Northeast	Canarana	Ferralsol Dystrophic	1960	27

440

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