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

M. Carauta[1]; I. Guzman-Bustamante[2]; K. Meurer[3]; A. Hampf[4]; C. Troost[1]; R. Rodrigues[5]; T. Berger[1];

1: University of Hohenheim, Land Use Economics in the Tropics and Subtropics, Germany, 2: University of Hohenheim, Fertilization and Soil Matter Dynamics, Germany, 3: Swedish University of Agricultural Sciences, Ecology

Corresponding author email: m.carauta@uni-hohenheim.de

Abstract:

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.

Acknowledgement: This research was financed by the CarBioCial project of the German Federal Ministry of Education and Research. We thankfully acknowledge the scholarships awarded by the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES) [grant number BEX-10421/14-9]. We are grateful to Embrapa Agrossilvipastoril and IMEA for the technical materials and knowledge provided. Special thanks to Eric Bönecke and Uwe Franko for their support on the parameterization of CANDY simulations. The simulation experiments were performed using the computational resources of bwUniCluster funded by the Ministry of Science, Research and the Arts and the Universities of the State of Baden-Württemberg, Germany.

JEL Codes: C63, Q01

#1027

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

Abstract

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.

1. Introduction

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

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

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

---

[1] Details omitted for double-blind reviewing.

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

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

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

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

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

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

2. Data and Methods

2.1. Study region and agricultural practices

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

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

Farmers can choose between multiple sowing dates, nitrogen amounts, seed maturity groups - herein MG - and, seed varieties (for example, farmers in different regions employ different types of pesticides and choose different intensity of machinery use, etc.). Crops with longer maturity cycles require more fungicide and insecticide applications; seed varieties require different pesticides (active ingredients), pesticide applications and quantities. A crop calendar with weekly resolution was created to capture the timing of agricultural activities at each survey site of IMEA. Detailed production technology analysis revealed more than 200 agricultural production activities that are combined with specific soil fertility constraints for each macro-region of IMEA, resulting in about 2000 crop-mix options at farm level. The complexity of farmer decision making increases even further as favorable climate conditions now allow flor a double cropping system, resulting in 40 feasible double crop combinations.

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

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

Fig. 1 Overview of agricultural practices in Mato Grosso

2.1.1. Typical production systems observed in Mato Grosso

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

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

2.2. Software used

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

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

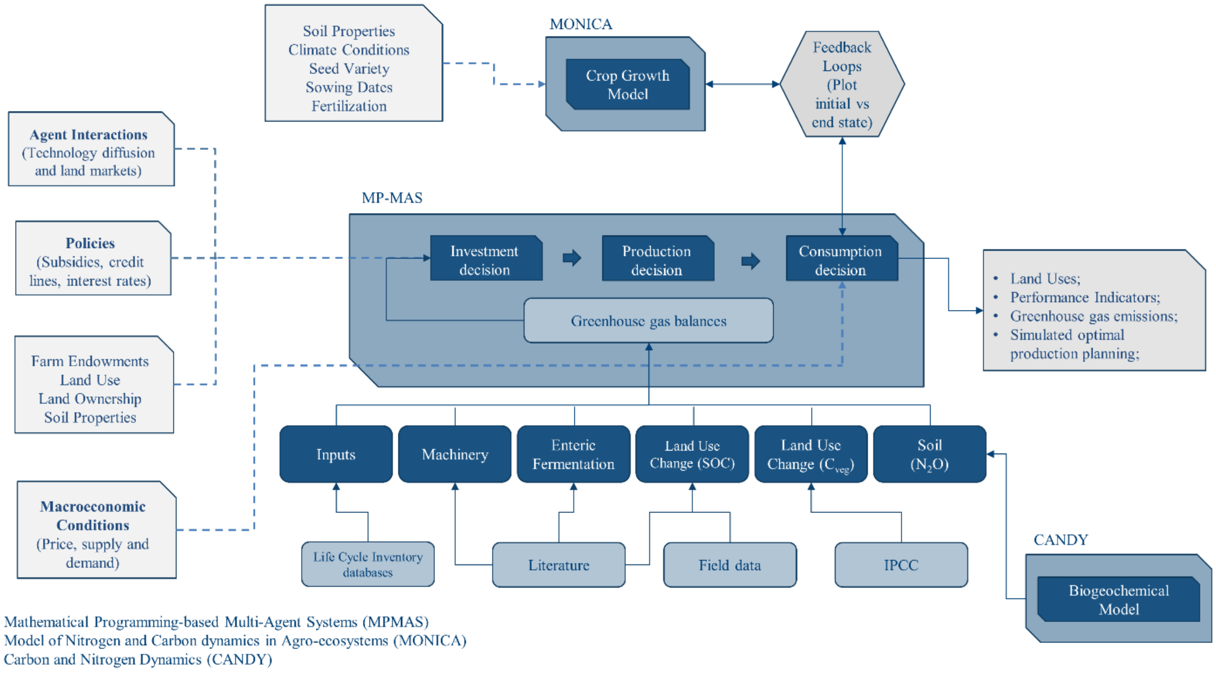

Fig. 2 Model flow chart and data sources

The main component of our IA application is the agent-based software package MPMAS which simulates farm-level decisions related to investment (i.e. which machinery to buy), production (i.e. which crops to grow) and consumption (i.e. how much to sell, withdraw or save for future periods) using Mixed Integer Linear Programming (MILP). For this current application, a statistically consistent agent population was created for the study region as described in Anonymous (2017). 844 farm agents maximize expected farm income recursively by solving 3 annual decision problems (investment, production, and consumption) over each period. Each agent's MILP consisted of 4,030 decision variables (162 integers) and 4,012 constraints. More details, such as software descriptions, model features, and ODD protocol can be found in Schreinemachers and Berger (2011).

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

The third software component is CANDY, a simulation model providing N_2O fluxes resulting from crop-soil management practices and subsequent effects on underlying biophysical processes, such as soil moisture. N_2O-N fluxes were simulated using an extended version of the CANDY model, which provides information about carbon (C) stocks in soil, organic matter turnover, nitrogen (N) uptake by crops, leaching, and water quality (Franko et al., 1995). This model has originally been developed in order to describe carbon turnover in agriculturally used soils under temperate conditions. Recently, the model has been used to reproduce observed N_2O-N fluxes from soils under Brazilian cattle pastures (Meurer et al., 2016) and cropland under soybean. Gaseous N losses are assumed to result from denitrification, which is regulated by soil moisture and soil temperature. The amount of emissions is a function of the size of the NO_3- pool, the amount of C in the active organic matter, and a denitrification factor. Since information about the initial soil carbon conditions at the various survey sites was lacking, we assumed the soil organic carbon to be in steady state according to the individual scenario. Thus, no changes of the soil carbon stocks (and resulting CO_2 fluxes) were included in our current simulations.

Based on the crop management decisions in MPMAS and the resultant crop yields simulated by MONICA, CANDY simulates daily nitrous oxide (N_2O) fluxes by taking into consideration all production systems at farm level, with specific crop rotation schemes, sowing dates, harvesting date, crop management practices, nitrogen application, stocking rates (exclusively for cattle systems) and local agroecological constraints (such as soil characteristics and weather conditions). In total, 27,170 annual GHG emission balances were simulated for 2,090 agent production decisions (combination of crop rotation practices and region-specific variables) over 14 years.

2.3. Specific LCA Data

Based on the approach proposed by Castanheira and Freire (2013), we established a life cycle GHG inventory for agricultural production systems for farms in MT. The system boundary was "cradle to gate" and GHG emission factors were estimated for inputs (fertilizers, pesticides, and others), machinery production, diesel consumption, soil processes (N_2O), land use change (annualized change of soil organic carbon - SOC - and carbon stock from vegetation - CVEG) and enteric fermentation (for cattle activities). All GHG were estimated as equivalents of carbon dioxide (CO_2e) using the global warming potential (GWP) conversion factors of each gas provided by the Intergovernmental Panel on Climate Change (IPCC) (Myhre et al., 2013).

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

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

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

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

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

N_2O emissions from soil microbiological processes for crop and cattle production are estimated with CANDY based on local crop management practices, fertilization amounts, soil characteristics and daily weather data. Emissions are estimated on a daily basis and cumulated for each crop, season, agricultural practice and region and then converted to carbon dioxide equivalent (CO_2e) using 298 as global warming potential factor (Myhre et al., 2013) N_2O emissions are simulated over a 14-year period (from 2000 to 2013) and the system was assumed to be in a steady-state. In order to avoid overestimation of N_2O emissions, the first five years of simulation have been excluded from our analysis.

N_2O emissions from urine and fecal deposition during grazing were also taken into consideration by CANDY. The biomass N pool is reduced due to grazing, which is influenced by the stocking rate and animal age. The CANDY model treats animal faeces as organic amendments that will influence soil organic matter and N_2O producing processes. Methane emissions from animal waste deposited on the field during grazing were not taken into account since, as pointed out by Cerri et al. (2016), a minimum quantity of CH_4 emission is expected from this source.

Forestry plantation N_2O emissions are estimated from an EMBRAPA (Brazilian Agricultural Research Corporation) field experiment located in Sinop, MT (Rodrigues et al., 2015) with an *eucalyptus* plantation under monoculture system. The hybrid *eucalyptus urograndhis* (H13) was planted in 2011 in an arrangement of 3,0 m x 3,5 m (952 trees ha^{-1}). Nitrous oxide samples were taken once a week, from November 2013 to October 2014 with the closed static chamber-based technique, in which change in gas concentration - determined by a gas chromatography - over time is used to calculate flux.

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

and SOC stocks of forest plantations are estimated with normal average from three literature sources (Inácio, 2009; Pulrolnik et al., 2009; Rangel and Silva, 2007). The difference in C stocks is amortized for 20 years, as recommended by Flynn et al. (2012), and converted to kilograms of CO_2e per year and hectare according to the following formula:

$$CO_2e_{\mathrm{LUC}}(R, LU) = (C\_initial_R - C\_actual_{LU}) \times \frac{M(CO_2)}{M(C)} \times \frac{1}{Period}$$

where CO_2e_{LUC} is the annualized GHG emission from changes in CVEG and SOC stocks due to LUC for each MT region (R) estimated in kilograms of CO_2e per hectare and year; C_*initial*$_{\mathrm{R}}$ is the initial SOC and CVEG stock for each MT macro-region (R); C_*actual*$_{\mathrm{LU}}$ is the actual SOC and CVEG stocks for each simulated land use (LU); $M(CO_2)$ is the molecular mass of CO_2 (44 g mol^{-1}); M(C) is the atomic mass of carbon (12 g mol^{-1}); and *Period* is the amortization period. Since in our current modeling setup farm agents are not allowed to clear their native forest land and their decision-making process refers to existing cropland only, initial C stocks are estimated based on cropland use.

Emissions from enteric fermentation are calculated according to the IPCC guidelines (IPCC, 2006), based on data from the *Second Brazilian Inventory of Anthropogenic Greenhouse Gas Emission* for methane emission factors under MT conditions (Lima et al., 2010) and weighted accordingly to each production system (animal category and sex). Emissions from enteric fermentation are estimated in kilogram of carcass by dividing it by live weight gain (in kg of live weight gain) - estimated with values taken from ANUALPEC (2013) - and multiplying it to carcass yield (which is estimated by local experts and depends on production system and intensity). All coefficients are then weighted by their cattle stocking rate (with three intensity levels: extensive, semi-intensive and intensive) and used to calculate carbon stocks for cattle production systems of agents simulated by MPMAS. Calculation of CO_2e is done by applying the 34 global warming potential for Methane (Myhre et al., 2013).

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

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

3. Simulation Results

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

3.1. Input and machinery emissions

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

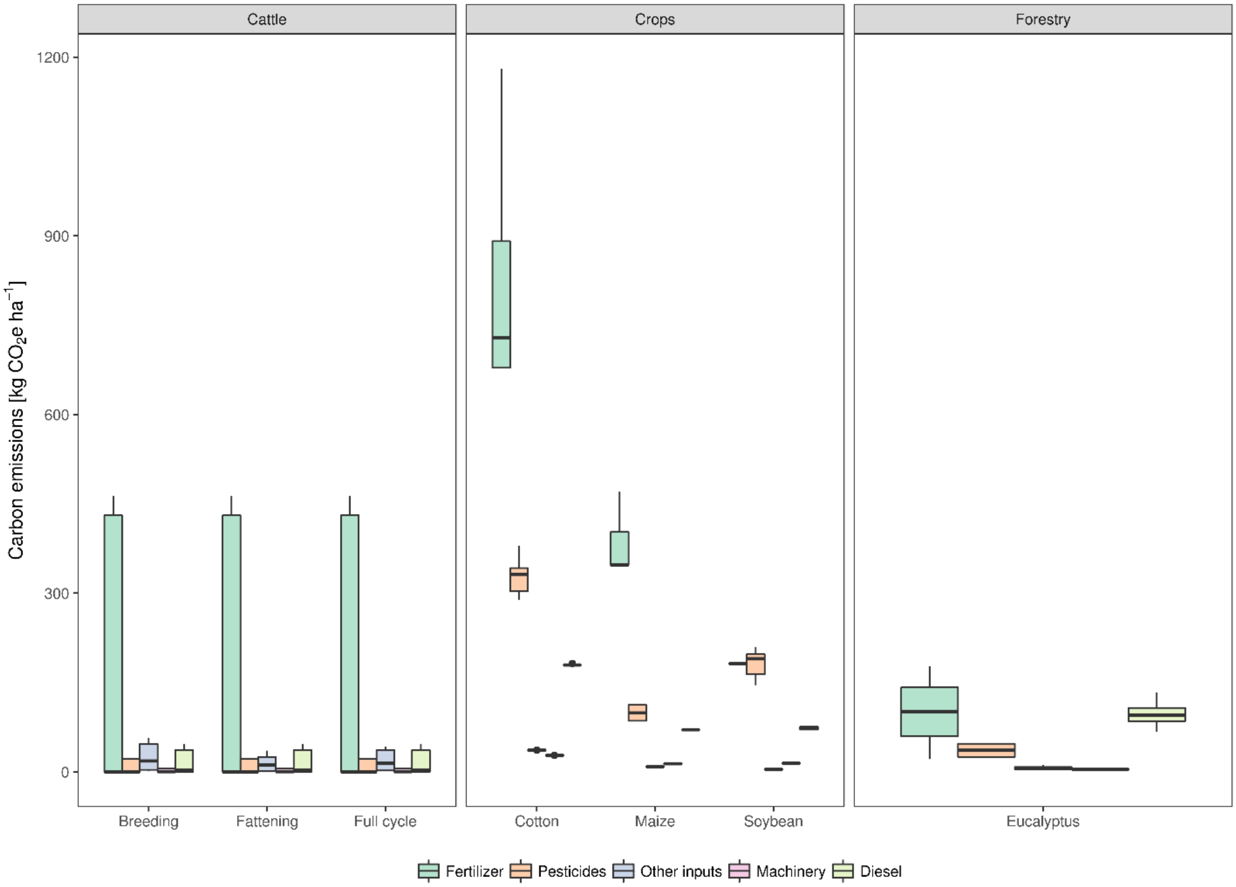

Fig. 3 Simulated GHG emissions for agricultural practices in Mato Grosso (Box plots)

3.2. Enteric emissions

Cattle emissions are simulated for different intensity levels, which are determined by specific coefficients, such as stocking rate (in animal units per hectare), pregnancy rate and grassland management (such as the use of fertilizers and pesticides for soil maintenance and correction). Emissions from enteric fermentation are shown in Fig. 4 for different production systems, intensities, and types of grassland. Emissions per kilogram of carcass from native grasslands are higher than from *brachiaria grasslands* since they have reduced yield rates due to lower forage production. The intensification process increases the absolute emission stocks but reduces the relative emission (emissions per kilogram of carcass) due to the reduction of the system's lifetime and the increase in the animal live weight gain. The main factors affecting enteric fermentation emissions are animal age and sex. Therefore, enteric emissions from extensive breeding systems are higher due to the higher share of cows while fattening system emissions are lower due to their higher share of young animals (mainly young bulls).

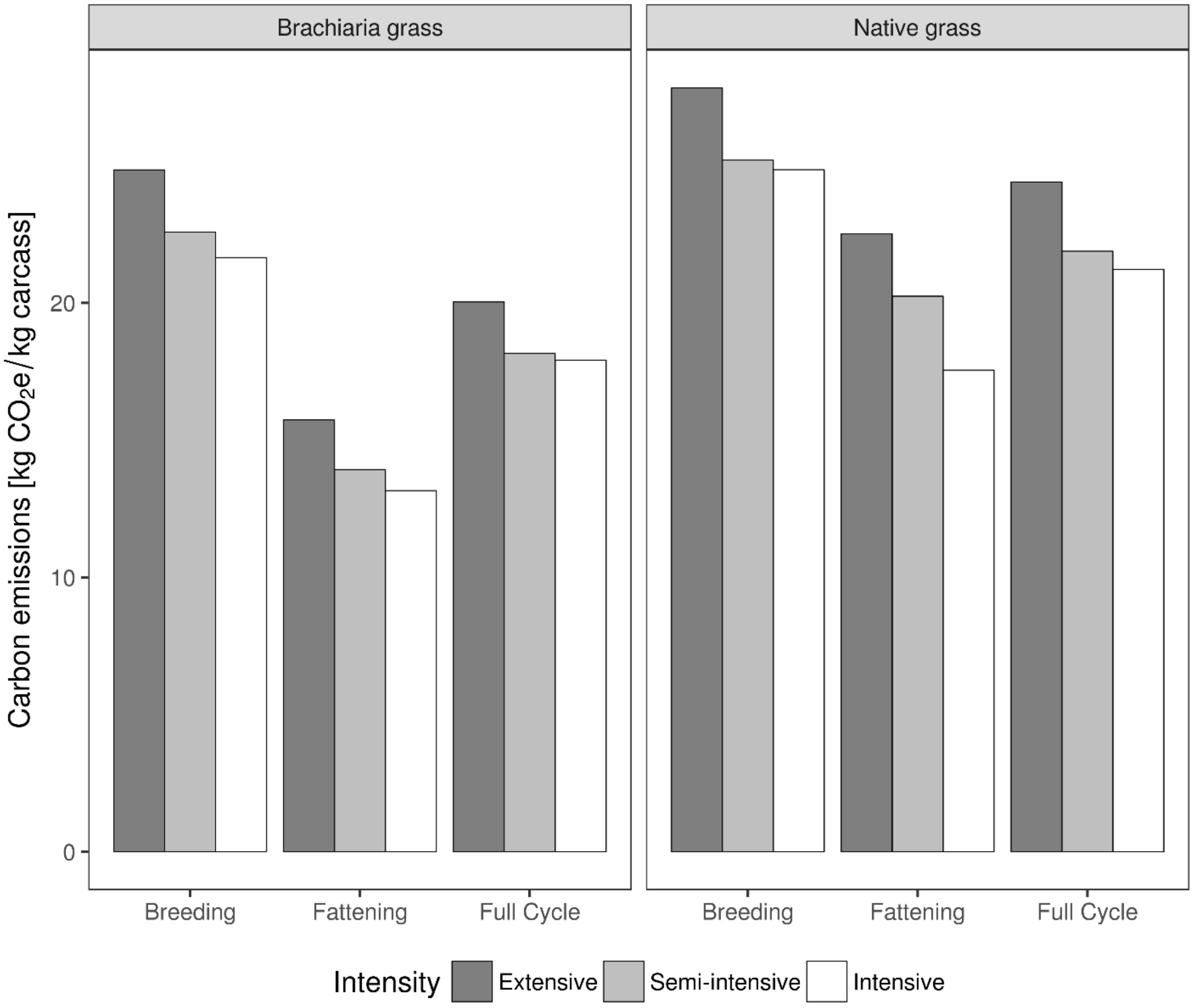

Fig. 4 Simulated GHG emissions of enteric fermentation for cattle production systems

3.3. Soil emissions

Fig. 4 depicts simulated values of nitrous oxide emissions estimated by CANDY and from field experiments over different agricultural practices in MT. Soil emissions from soybean and cotton are, on average, higher than maize due to the high use of fertilizers on those crop rotations. Variables which mostly influence N_2O emissions are soil type (higher emissions from loamy, clayey soils) and the applied nitrogen amount (high emissions with higher nitrogen rate amounts).

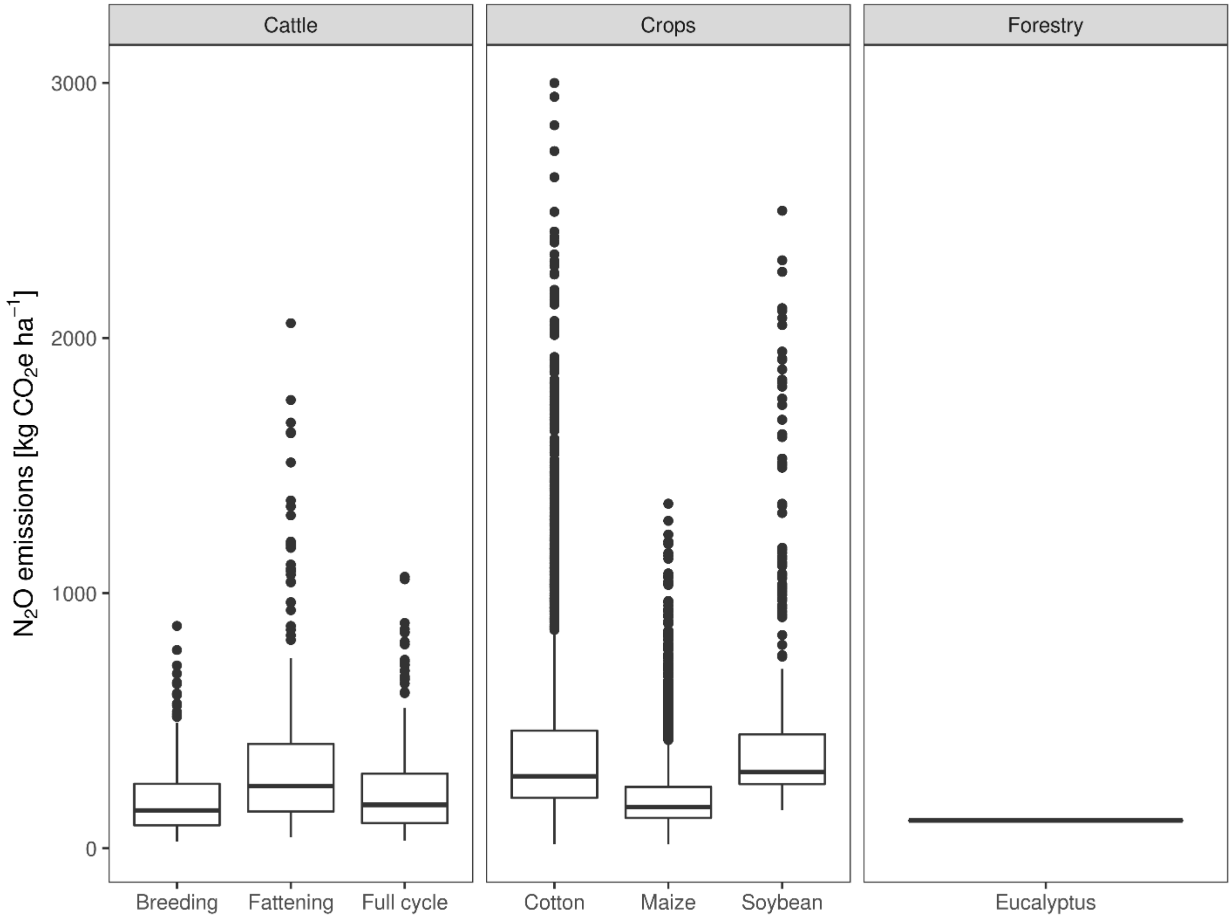

Fig. 5 Simulated soil nitrous oxide emissions (Box plots)

3.4. Land use change emissions

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

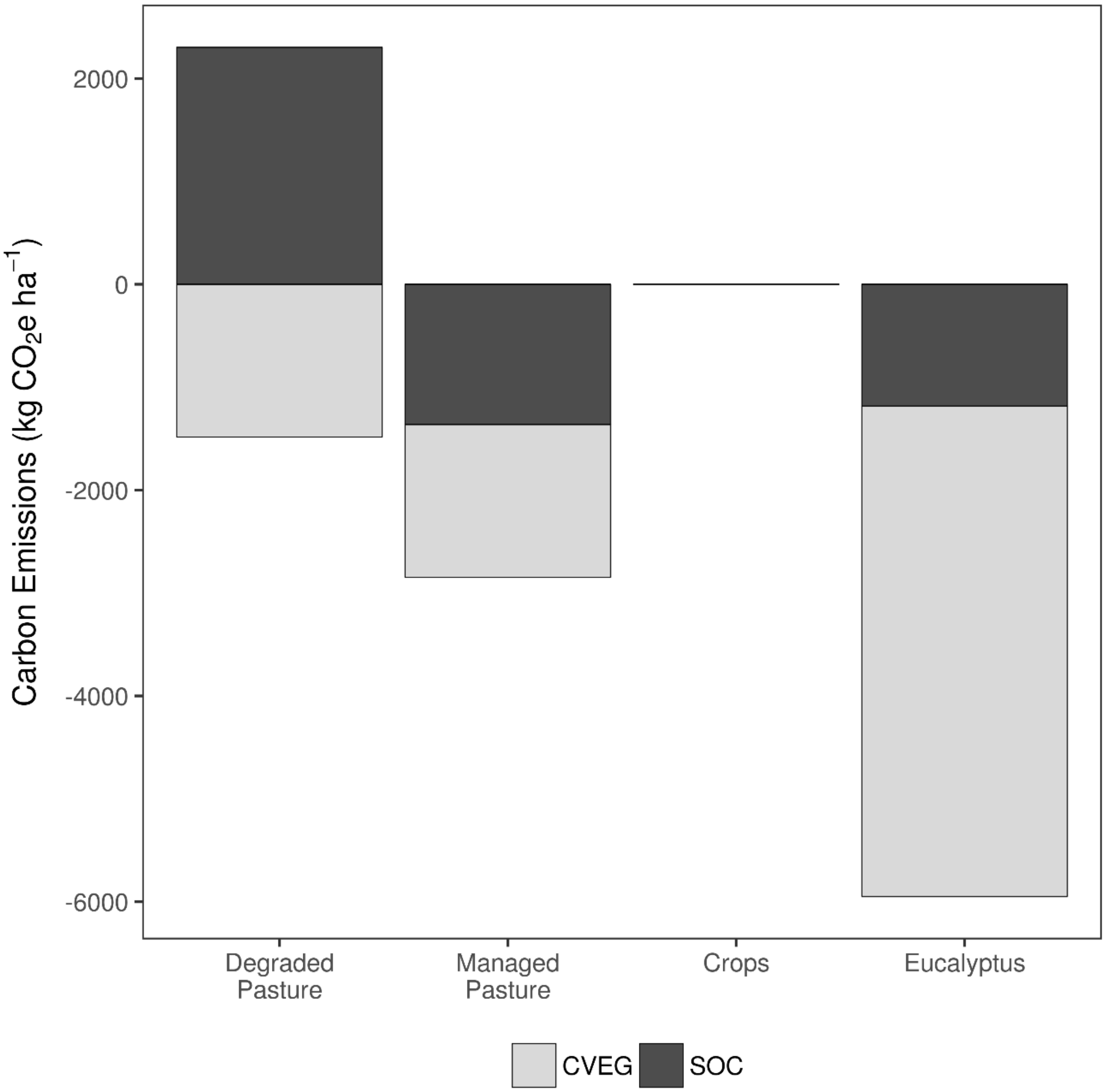

Fig. 6 Simulated GHG emissions related to changes in soil organic carbon (SOC) and carbon stock from vegetation (CVEG). Reference point: Cropland land use

3.5.Carbon footprint for typical production practices in Mato Grosso

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

CO_2e per hectare and year. Forestry production in our simulations showed the lowest values due to their high share of carbon sequestration from land use change. Cropping systems presented only positive GHG emissions since there is no negative effect of land use conversion for these systems. Among cropping systems, cotton production showed the highest emissions due to its high input use. Extensive cattle production systems ("degraded pasture") showed the highest net emissions due to enteric fermentation and land use change emissions.

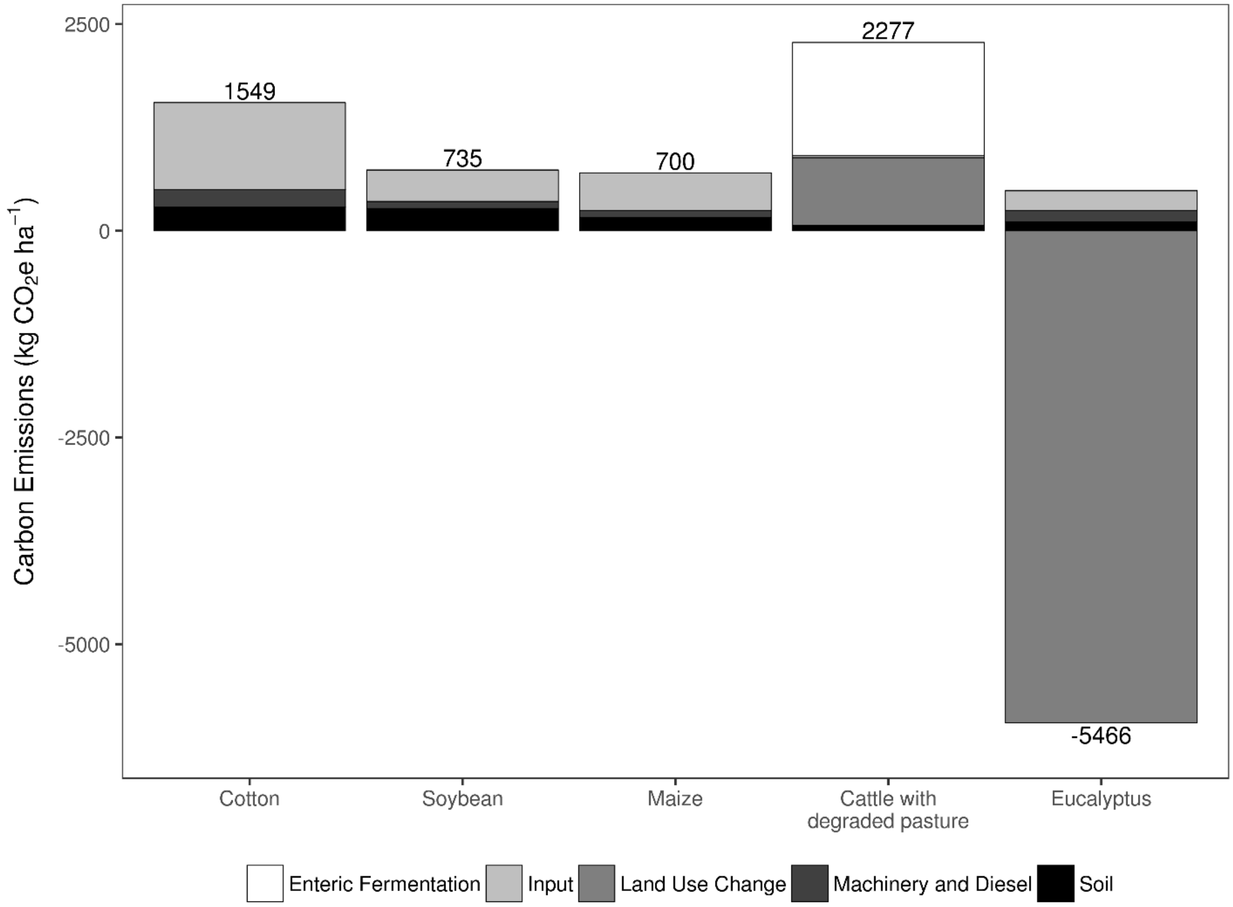

Fig. 7 Simulated total GHG emissions for typical production systems in Mato Grosso

3.6. Primary GHG emissions for production practices in Mato Grosso

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

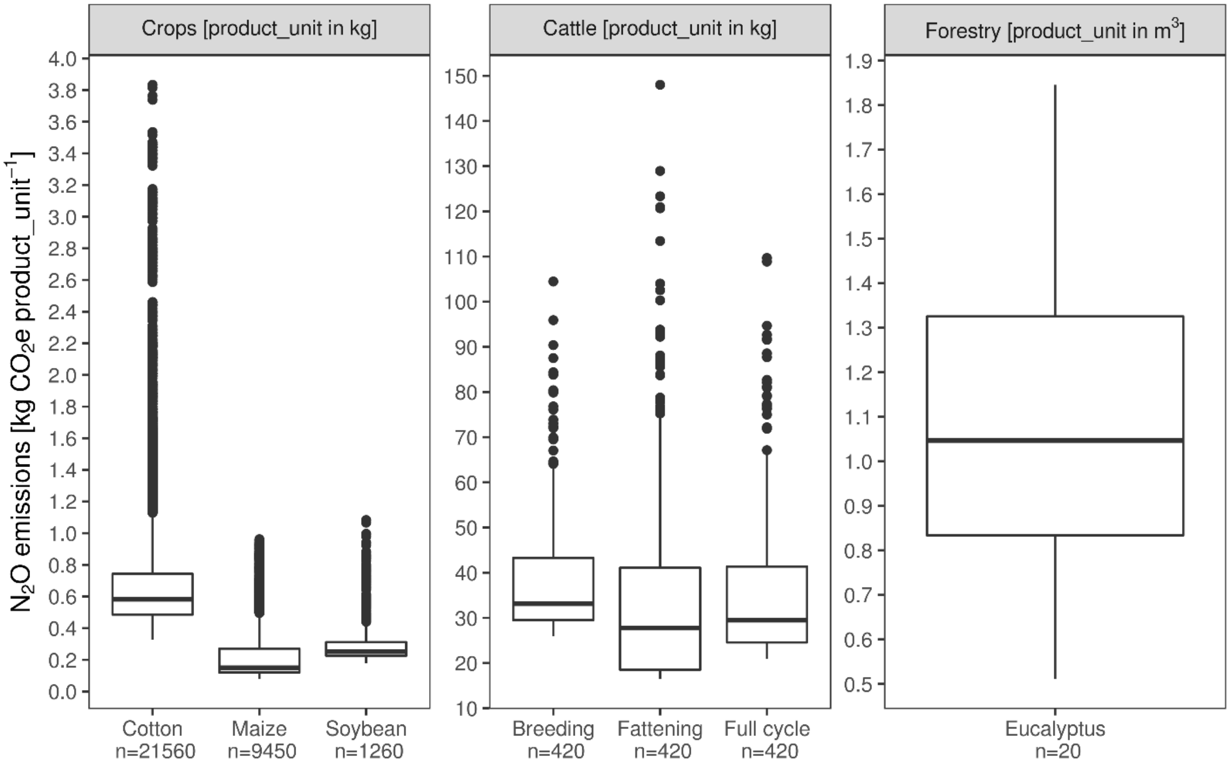

Fig. 8 Simulated GHG emissions in carbon dioxide equivalents per product unit for different production systems (n = number of observations).

4. Discussion

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

Our GHG emissions from primary production (not including emissions from LUC) for a typical (=median) cattle production system were estimated at approximately 21 kg CO_2e per kg of CW (carcass weight), which is lower than the national average value of 28 kg CO_2e per kg of CW estimated by Cederberg et al. (2009). This underlines the importance of evaluating GHG emissions over the full range of agricultural practices, where the median represents a skewed distribution better than the arithmetic mean. Cerri et al. (2016) and Cederberg et al. (2009) indicate that the largest source of GHG emissions in beef production comes directly from the animal feeding. Fig. 7 confirms this by displaying enteric fermentation as the main source of emission in cattle production (after land use change) – an emission source not considered by most other empirical studies. As an example, Cederberg et al. (2011) argue that the omission of land use change emissions can lead to serious underestimates, especially for meat production.

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

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

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

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

5. Conclusions

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

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

The amplitude of our simulated carbon footprints suggests that GHG emissions are sensitive to several social and environmental variables/constraints which are (so far) difficult to represent in current LCA studies. This result underlines the importance of novel approaches that are capable to capture those variables and constraints and their impact on farmers decision-making.

Appendix

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

Site No.	**Macro-region**	**Survey Site**	**Soil type [WRB]**	**MAP [mm]**	**MAT [ºC]**
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

References

[Anonymous 2017] Details omitted for double-blind reviewing.

Anuário da Pecuária Brasileira (ANUALPEC), 2013. *Anuário da Pecuária Brasileira.* AGRA FNP Pesquisas LTDA, São Paulo, Brazil.

Argonne National Laboratory, 2015. *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model.* The University of Chicago.

Azapagic, A., 2017. *CCaLC: Carbon Calculations over the Life Cycle of Industrial Activities.* The University of Manchester.

Braz, S. P., Urquiaga, S., Alves, B. J.R., Jantalia, C. P., Guimarães, A. P., dos Santos, C. A., dos Santos, S. C., Machado Pinheiro, É. F., Boddey, R. M., 2013. Soil Carbon Stocks under Productive and Degraded Pastures in the Brazilian Cerrado. *Soil Science Society of America Journal*. **77**, 914.

Brazilian Agricultural Research Corporation (EMBRAPA), 2016. Adoção de ILPF chega a 11,5 milhões de hectares - Portal Embrapa. Accessed May 2017, available at https://www.embrapa.br/busca-de-noticias/-/noticia/17755008/adocao-de-ilpf-chega-a-115-milhoes-de-hectares.

Castanheira, É. G., Freire, F., 2013. Greenhouse gas assessment of soybean production. Implications of land use change and different cultivation systems. *Journal of Cleaner Production.* **54**, 49–60.

Cederberg, C., Meyer, D., Flysjö, A., 2009. Life cycle inventory of greenhouse gas emissions and use of land and energy in Brazilian beef production, available at http://www.diva-portal.org/smash/get/diva2:943348/FULLTEXT01.

Cederberg, C., Persson, U. M., Neovius, K., Molander, S., Clift, R., 2011. Including carbon emissions from deforestation in the carbon footprint of Brazilian beef. *Environmental science & technology*. **45**, 1773–1779.

Cerri, C. C., Moreira, C. S., Alves, P. A., Raucci, G. S., Almeida Castigioni, B. de, Mello, F. F.C., Cerri, D. G. P., Cerri, C. E. P., 2016. Assessing the carbon footprint of beef cattle in

Brazil. A case study with 22 farms in the State of Mato Grosso. *Journal of Cleaner Production.* **112**, 2593–2600.

Companhia Nacional de Abastecimento (CONAB), 2010. Custos de Produção Agrícola. A metodologia da Conab. Accessed March 2017, available at http://www.conab.gov.br/conabweb/download/safra/custos.pdf.

Companhia Nacional de Abastecimento (CONAB), 2017. Séries Históricas de Área Plantada, Produtividade e Produção, Relativas às Safras 1976/77 a 2015/16 de Grãos. Accessed January 2017, available at http://www.conab.gov.br/conteudos.php?a=1252.

European Commission, 2010. Commission Decision of 10 June 2010 on guidelines for the calculation of land carbon stocks for the purpose of Annex V to Directive 2009/28/EC. Notified under document C(2010) 3751. Accessed March 2017, available at http://www.ebb-eu.org/sustaindl/EC%20Decision%20land%20carbon%20stocks%20June%202010.pdf.

Federação da Agricultura e Pecuária do Estado de Mato Grosso (FAMATO), 2013. *Diagnóstico de Florestas Plantadas do Estado de Mato Grosso.* Federação da Agricultura e Pecuária do Estado de Mato Grosso (FAMATO), Cuiabá, Brazil.

Fialho, R. C., Zinn, Y. L., 2014. CHANGES IN SOIL ORGANIC CARBON UNDER EUCALYPTUS PLANTATIONS IN BRAZIL. A COMPARATIVE ANALYSIS. *Land Degrad. Develop.* **25**, 428–437.

Flynn, H. C., Canals, L. M. i., Keller, E., King, H., Sim, S., Hastings, A., Wang, S., Smith, P., 2012. Quantifying global greenhouse gas emissions from land-use change for crop production. *Glob Change Biol.* **18**, 1622–1635.

Fonte, S. J., Nesper, M., Hegglin, D., Velásquez, J. E., Ramirez, B., Rao, I. M., Bernasconi, S. M., Bünemann, E. K., Frossard, E., Oberson, A., 2014. Pasture degradation impacts soil phosphorus storage via changes to aggregate-associated soil organic matter in highly weathered tropical soils. *Soil Biology and Biochemistry.* **68**, 150–157.

Franko, U., Oelschlägel, B., Schenk, S., 1995. Simulation of temperature-, water- and nitrogen dynamics using the model CANDY. *Ecological Modelling.* **81**, 213–222.

Garrett, R. D., Niles, M. T., Gil, J.D.B., Gaudin, A., Chaplin-Kramer, R., Assmann, A., Assmann, T. S., Brewer, K., Faccio Carvalho, P. C. de, Cortner, O., Dynes, R., Garbach, K., Kebreab, E., Mueller, N., Peterson, C., Reis, J. C., Snow, V., Valentim, J., 2017. Social and ecological analysis of commercial integrated crop livestock systems. Current knowledge and remaining uncertainty. *Agricultural Systems.* **155**, 136–146.

Gil, J., Siebold, M., Berger, T., 2015. Adoption and development of integrated crop–livestock–forestry systems in Mato Grosso, Brazil. *Agriculture, Ecosystems & Environment.* **199**, 394–406.

Gil, J.D.B., Garrett, R., Berger, T., 2016. Determinants of crop-livestock integration in Brazil. Evidence from the household and regional levels. *Land Use Policy.* **59**, 557–568.

Hanson, J. D., Franzluebbers, A., 2008. Principles of integrated agricultural systems. *Renew. Agric. Food Syst.* **23**, 263–264.

Hendrickson, J. R., Hanson, J. D., Tanaka, D. L., Sassenrath, G., 2008a. Principles of integrated agricultural systems. Introduction to processes and definition. *Renew. Agric. Food Syst.* **23**, 265–271.

Hendrickson, J. R., Liebig, M. A., Sassenrath, G. F., 2008b. Environment and integrated agricultural systems. *Renew. Agric. Food Syst.* **23**, 304–313.

Inácio, E., 2009. *Distribuição vertical de carbono orgânico em Latossolo sob diferentes usos.* UNIVERSIDADE FEDERAL DE LAVRAS, Lavras, Brazil.

Instituto Mato-Grossense de Economia Agropecuária (IMEA), 2010. Macroregion methodology report of Mato Grosso. Accessed March 2017, available at http://www.imea.com.br/upload/publicacoes/arquivos/justificativamapa.pdf.

Instituto Mato-Grossense de Economia Agropecuária (IMEA), 2013. Production cost survey from the Mato Grosso Institute of Agricultural Economics (IMEA). Accessed March 2017, available at http://www.imea.com.br/imea-site/relatorios-mercado.

Instituto Mato-Grossense de Economia Agropecuária (IMEA), 2016. Panorama da pecuária de Mato Grosso.

Instituto Mato-Grossense de Economia Agropecuária (IMEA), 2017. Instituto Mato-grossense de Economia Agropecuária (Mato Grosso Institute of Agricultural Economics). Accessed January 2017, available at www.imea.com.br.

Intergovernmental Panel on Climate Change (IPCC), ed., 2006. *IPCC Guidelines for National Greenhouse Gas Inventories*. Institute for Global Environmental Strategies, Japan.

Lima, M. A., Pessoa, Maria da conceição P. Y., Neves, M. C., Carvalho, H. C., 2010. Emissões de Metano por Fermentação Entérica e Manejo de Dejetos de Animais, available at https://www.alice.cnptia.embrapa.br/alice/bitstream/doc/921485/1/2011MZ02.pdf.

Meurer, K. H.E., Franko, U., Spott, O., Stange, C. F., Jungkunst, H. F., 2016. Model testing for nitrous oxide (N2O) fluxes from Amazonian cattle pastures. *Atmospheric Environment*. **143**, 67–78.

Ministério da Agricultura, Pecuária e Abastecimento (MAPA), 2017. Brazilian Trade Balance and Agribusiness Trade Balance: 1989 to 2015, available at http://www.agricultura.gov.br/assuntos/relacoes-internacionais/documentos/estatisticas-do-agronegocio/serie-historica-bca-resumida-1997-2016.xls.

Ministério da Ciência, Tecnologia, Inovações e Comunicações (MCTI), 2016. Third National Communication of Brazil to the United Nations Framework Convention on Climate Change, available at http://sirene.mcti.gov.br/documents/1686653/1706740/MCTI_volume_III_ingles.pdf/65897db2-8501-425f-824e-bc6844492e61.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and Natural Radiative Forcing, in T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, eds. *Climate Change 2013: The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659–740.

Nendel, C., Berg, M., Kersebaum, K. C. C., Mirschel, W., Specka, X., Wegehenkel, M., Wenkel, K. O. O., Wieland, R., 2011. The MONICA model: Testing predictability for crop growth, soil moisture and nitrogen dynamics. *Ecological Modelling.* **222**, 1614–1625.

Nogueira, A. K. d. S., Rodrigues, R. d. A. R., Castro, B. S., Nogueira, T. F., Silva, J. J. N. d., Behling, M., Mombach, M., Armacolo, N., Silveira, J. G., 2015. EMISSION OF NITROUS OXIDE AND METHANE IN SOIL FROM PASTURE RECOVERY AREAS IN THE AMAZON MATOGROSSENSE. *Química Nova*.

Observatório ABC, 2016. Análise dos Recursos do Programa ABC. Instituições financeiras privadas. Accessed June 2017, available at http://observatorioabc.com.br/wp-content/uploads/2016/10/Relatorio-Completo_Análise-dos-Recursos-ABC-safra1516.pdf.

Pulrolnik, K., Barros, N. F. d., Silva, I. R., Novais, R. F., Brandani, C. B., 2009. Estoques de carbono e nitrogênio em frações lábeis e estáveis da matéria orgânica de solos sob eucalipto, pastagem e cerrado no Vale do Jequitinhonha - MG. *Revista Brasileira de Ciência do Solo.* **33**, 1125–1136.

Rangel, O. J. P., Silva, C. A., 2007. Estoques de carbono e nitrogênio e frações orgânicas de Latossolo submetido a diferentes sistemas de uso e manejo. *Revista Brasileira de Ciência do Solo.* **31**, 1609–1623.

Raucci, G. S., Moreira, C. S., Alves, P. A., Mello, F. F.C., Frazão, L. d. A., Cerri, C. E. P., Cerri, C. C., 2015. Greenhouse gas assessment of Brazilian soybean production. A case study of Mato Grosso State. *Journal of Cleaner Production.* **96**, 418–425.

Rodrigues, R., Silveira, J. G., Nogueira, A. K., Silva, J. J. Da N. Da, Botin, A. A., Mombach, M. A., Armacolo, N. M., Pirolla, M. L. A., 2015. Nitrous oxide emissions in eucalyptus production under monoculture and integrated systems in Sinop (MT), in Brazilian Agricultural Research Corporation (EMBRAPA), ed. *Proceedings of the World Congress on Integrated Crop-Livestock-Forest Systems: Towards sustainable intensification*.

Rotz, C. A., Montes, F., Chianese, D. S., 2010. The carbon footprint of dairy production systems through partial life cycle assessment. *Journal of dairy science.* **93**, 1266–1282.

Schreinemachers, P., Berger, T., 2011. An agent-based simulation model of human-environment interactions in agricultural systems. *Environmental Modelling and Software.* **26**, 845–859.

Strey, S., Boy, J., Strey, R., Weber, O., Guggenberger, G., 2016. Response of soil organic carbon to land-use change in central Brazil. A large-scale comparison of Ferralsols and Acrisols. *Plant Soil.* **408**, 327–342.

Torres, C. M.M. E., Kohmann, M. M., Fraisse, C. W., 2015. Quantification of greenhouse gas emissions for carbon neutral farming in the Southeastern USA. *Agricultural Systems.* **137**, 64–75.

Troost, C., Berger, T., 2015. Dealing with Uncertainty in Agent-Based Simulation. Farm-Level Modeling of Adaptation to Climate Change in Southwest Germany. *Am J Agric Econ.* **97**, 833–854.