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Climate-related land use policies in Brazil: How much has been achieved with economic incentives in agriculture?

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ABSTRACT

Until 2019, the Brazilian federal government employed a number of policy measures to fulfill the pledge of reducing greenhouse gas emissions from land use change and agriculture. While its forest law enforcement strategy was partially successful in combating illegal deforestation, the effectiveness of positive incentive measures in agriculture has been less clear. The reason is that emissions reduction from market-based incentives such as the Brazilian Low-Carbon Agriculture Plan cannot be easily verified with current remote sensing monitoring approaches. Farmers have adopted a large variety of integrated land-use systems of crop, livestock and forestry with highly diverse per-hectare carbon balances. Their responses to policy incentives were largely driven by cost and benefit considerations at the farm level and not necessarily aligned with federal environmental objectives. This article analyzes climate-related land-use policies in the state of Mato Grosso, where highly mechanized soybean–cotton and soybean–maize cropping systems prevail. We employ agent-based bioeconomic simulation together with life-cycle assessment to explicitly capture the heterogeneity of farm-level costs, benefits of adoption, and greenhouse gas emissions. Our analysis confirms previous assessments but suggests a smaller farmer policy response when measured as increase in area of integrated systems. In terms of net carbon balances, our simulation results indicate that mitigation effects at the farm level depended heavily on the exact type of livestock and grazing system. The available data were insufficient to rule out even adverse effects. The Brazilian experience thus offers lessons for other land-rich countries that build their climate mitigation policies on economic incentives in agriculture.

1. Introduction

In 2009, the Brazilian government pledged to reduce its greenhouse gas (GHG) emissions and implemented national mitigation policies the year after. Since a large share of Brazil's emissions – approx. 35% according to MCTI (2016) – came from agriculture, the government launched the ABC Plan (Low-Carbon Agriculture Plan, in Portuguese: *Plano de Agricultura de Baixo Carbono*). The ABC Plan has incentivized low-carbon agricultural practices by financing – among other measures – the adoption of so-called integrated systems with subsidized credit.

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Integrated systems combine crop-livestock-forestry production in various land-use configurations at farm level and are supposedly more carbon-friendly (Garrett et al., 2017). Reports from Observatório ABC (2016), however, suggest that this climate-related financing program did not achieve its full potential. During the 2015/2016 cropping season, the program distributed only 68% of the total amount earmarked by the federal government. Moreover, the degree to which the ABC credit program could actually induce reductions of GHG emissions from agriculture remains unclear.[1]

Research into GHG emissions by Brazilian agriculture is advancing, but only few empirical studies focused on Mato Grosso (MT), the hotspot of national crop and cattle production. Cerri et al. (2016) evaluated the main sources of GHG emissions in beef production systems for 22 farms in MT, while Observatório ABC (2017) evaluated nitrous oxide emissions in three beef production field experiments in the north of MT. Raucci et al. (2015) conducted a life-cycle assessment of soybean cultivation for 55 farms in MT, and Castanheira and Freire (2013) investigated the life-cycle GHG balance of soybean produced in Latin America through different scenarios of land use, cultivation, and transportation. Gil et al. (2018) simulated GHG emissions for one medium-size representative farm in MT, comparing 4 cattle production systems under 2 different climate scenarios using whole-farm modeling.

This paper contributes to the available literature by applying a novel assessment approach that evaluates real-world agricultural production systems at the farm level, combining life-cycle assessment for GHG emissions and counterfactual bioeconomic simulation. Agroecological conditions within Mato Grosso differ considerably, and farmers adjust their crop management especially in terms of fertilizer and pesticide applications. This large heterogeneity requires process-based soil-crop-farm modeling to simulate response functions and GHG emissions for all relevant land-use options at various locations. The main component of our approach is an agent-based simulation model that links socio-economic and biophysical constraints with very high spatial resolution and, thereby, simulates farmer decision-making and policy uptake. We estimate the GHG emissions for a wide range of farm production systems to evaluate the impact of the ABC Credit Program. This is the first study in Mato Grosso to assess market-based climate measures considering economic decision-making, environmental heterogeneity, and life-cycle assessment at the farm level.

2. Measuring the impact of incentive-based policies

Climate-related land-use policy can draw on a wide range of instruments from regulatory and voluntary measures to positive and negative incentives. Until 2019, the Brazilian federal government employed a mix of these measures to fulfill the pledge of reducing greenhouse gas emissions from land use change and agriculture. While its forest law enforcement strategy was to a certain extent successful in combating illegal deforestation (Tacconi et al., 2019), the effectiveness of positive incentive measures in agriculture has been less clear (Gil et al., 2016). This is because emissions reduction related to market-based incentives such as the ABC Plan cannot easily be verified with current remote-sensing monitoring approaches. Farmers typically adopt a large variety of integrated land-use systems of crop, livestock and forestry with highly diverse per-hectare GHG balances (Gil et al., 2015). Measuring the farm-level impact of ABC credit in this policy setting would require detailed individual farm data of those individuals who adopted and those who did not. Such policy experiment data, however, are not available for Brazilian agriculture; statistical policy impact analysis is therefore not possible (Antle, 2019).

Apart from limited data availability, which is typically addressed by data fusion and injection of expert knowledge, the core challenge is to deduce what farmers would have done without the policy. As discussed by Berger and Troost (2014), counterfactuals for land-use policy analysis can be simulated with farm-level agent-based modeling. This modeling technique uses mathematical programming (MP) and builds on a long application history in Agricultural Economics. MP is a planning approach used in farm management that helps find the assignment of farm resources (land, labor, machinery) to various land-use options (grow crops, graze livestock) such that given objectives (increase income, reduce risks) can be achieved as best as possible. MP planning principles are widely taught at farm management schools and match the way how farmers internally conceptualize their decision problems. While the purpose of MP was initially prescriptive, giving farmers recommendations on how to improve their productivity, whole-farm MP models can also be developed for descriptive and predictive purposes, e.g. to simulate actual farmer behavior and especially for policy assessment (Hazell and Norton, 1986). To capture the large heterogeneity of farmer policy responses and interactions, Balmann (1997) and Berger (2001) started combining MP modeling with agent-based simulation, which was later developed into a computationally efficient approach for high-performance computing (Troost and Berger, 2015). Today, agent-based simulation using MP has reached acceptance as a modeling approach in agriculture with a wide variety of applications around the word (Kremmydas et al., 2018; Utomo et al., 2018). The agent-based simulation package MPMAS described in Schreinemachers and Berger (2011), for example, has been applied in 11 countries for integrated assessment and policy analysis (Berger et al., 2007; Schreinemachers et al., 2007; Quang et al., 2014; Wossen et al., 2014; Grovermann et al., 2017).

This study also uses MPMAS, following up on the applications in Carauta et al. (2017) and Hampf et al. (2018). As novelties, it (i) combines counterfactual bioeconomic simulation with life-cycle assessment and extensive model uncertainty analysis using high-performance computing, and (ii) assesses the impact of climate-related policy measures in reducing GHG emissions from agriculture.

3. Data and methods

3.1. Study area

The federal state of Mato Grosso, covering an area of France and Germany combined, supplies about one quarter of Brazil's soybean, maize, cotton, and cattle production (CONAB, 2017). Ecologically, Mato Grosso has native vegetation in three different ecosystems: the Amazon rainforest, the *Pantanal* wetlands, and the *Cerrado* bushland, which together comprise more than half of the state's territory (IBGE, 2018). As in Carauta et al. (2017) and Hampf et al. (2018), we applied the sampling procedure of IMEA (2017) and parameterized our simulation models for their representative sites in five macro-regions. In these five macro-regions, highly mechanized large-scale farm holdings produce almost the entire agricultural output of Mato Grosso.

3.2. Production systems

We compiled crop calendars with weekly resolution to capture the timing of agricultural activities for each survey site of IMEA. Farmers usually practice double-cropping: soybean is sown at the onset of the rainy season, whereas maize is sown in succession and harvested in the dry season. Cotton is typically cultivated as an alternative to maize after soybean or after a cover crop such as millet or sorghum. Detailed production technology analysis revealed more than 200 management options (e.g., soil preparation, crop variety, sowing date, harvest date, and fertilization level) that are combined with specific soil fertility constraints for each IMEA site, yielding about 2000 crop production activities at farm level.

Cattle production systems in Mato Grosso are based on large-scale

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[1] The new federal government continued the ABC credit program in 2019 and has made available 2.5 billion Brazilian Reais (BRL) for the cropping season 2020/21, an increase by 400 million compared to the previous year.

extensive grazing and they either focus on cattle fattening and beef production or on cattle breeding (Cohn et al., 2016). We considered about 20 cattle production systems with different intensity levels (stocking rates), grazing inputs (*Brachiaria brizantha* or unmanaged native grassland), and production set-ups (breeding, fattening, or full cycle with both breeding and fattening).

In terms of forestry production systems, we specified three different systems with eucalyptus (*Eucalyptus urograndis*) based on 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 produces only wood and has a 14-year production cycle. Costs and benefits of local production systems were estimated from 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 additional input from local experts.

3.3. *Model components*

In order to evaluate a wide range of crop, livestock, and forestry production systems at farm level, we applied an integrated assessment (IA) approach using three simulation packages (Fig. 1): MPMAS (Mathematical Programming-based Multi-Agent Systems), MONICA (Model for Nitrogen and Carbon in Agro-ecosystems) and CANDY (Carbon and Nitrogen Dynamics). We advanced the modeling approach published in Carauta et al. (2017) and Hampf et al. (2018) by incorporating life-cycle GHG balances in the present simulations. Since a detailed explanation of model parameterization and model validation is already available in these two articles and in our Supplementary material,[2] only a brief overview of our integrated modeling system is given here.

The main component of our IA application is the agent-based software package MPMAS, which simulates farm-level decisions related to investment (e.g. which machinery to buy), production (e.g. which crops to grow), and consumption (e.g. how much to sell, withdraw, or save for future periods) using Mixed Integer Linear Programming (MILP). A detailed software description with model features and ODD protocol is provided in Schreinemachers and Berger (2011). For this current application, we created a statistically consistent agent population with 844 farm agents – corresponding to 99% of all crop-producing farms at the IMEA sites in terms of agricultural area and 74% in terms of number.[3] Farm agents in MPMAS maximize expected farm income recursively by solving 3 annual decision problems (investment, production, and consumption) over each period. Each agent's MILP consists of 4030 decision variables (162 integers) and 4012 constraints.

The second component of our IA application is the process-based crop growth model MONICA, which was used to simulate crop yields of different cultivars in response to different nitrogen fertilization rates, soil types, and climatic conditions. By integrating MPMAS and MONICA, technical and environmental constraints can be captured at the individual farm level and, thus, enable assessing agent decision-making and policy response subject to specific local environmental conditions. At the investment and production stages, farm agents in MPMAS decide what 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 actual crop prices received for a given year. Further model details and software specifications of MONICA are described in Nendel et al. (2011). In total, 420 local crop yields were simulated for soybean, 6300 for maize, and 10,780 for cotton using detailed weather data from 2000 to 2013.

The third software component is CANDY, a process-oriented biogeochemical simulation model providing nitrous oxide (N_2O) fluxes resulting from crop-soil management practices and subsequent effects on underlying biophysical processes. N_2O—N fluxes were simulated using an extended version of CANDY, 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 was originally developed to describe carbon turnover in agriculturally used soils under temperate conditions. The model has recently been extended to reproduce observed N_2O—N fluxes from soils under Brazilian cattle pastures (Meurer et al., 2016) and cropland, and to evaluate N_2O—N emissions under different crop rotations in Mato Grosso (Meurer et al., 2019). 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 NO_3-pool size, the amount of C in active organic matter, and a denitrification factor. Based on the agent crop management decisions in MPMAS and the resulting crop yields simulated by MONICA, CANDY simulates daily N_2O fluxes by considering all production systems at farm level, with specific crop rotational schemes, sowing and harvest dates, crop management practices, nitrogen application, stocking rates for cattle systems, and local agroecological constraints (such as soil characteristics and weather conditions).

The nitrous oxide flows simulated by CANDY are one component of the life-cycle inventory of GHG emissions that we calculated for each production activity. Our assessment considered all emissions from cradle to farm gate. Emission factors for fertilizers, pesticides, and other inputs were taken from Azapagic (2017) and Argonne National Laboratory (2015). Emission factors for farm machinery employed comprised emissions from machinery production based on Rotz et al. (2010) and emissions from fuel consumption based on CONAB (2010) and Frischknecht et al. (2005). For livestock production, methane emissions from enteric fermentation were retrieved from Lima et al. (2010). Moreover, we calculated above- and below-ground carbon stocks combining data on vegetation carbon stocks from IPCC (2006), data on soil organic carbon (SOC) stocks of cropland, degraded and managed pasture from Strey et al. (2016), as well as data on SOC stocks of forestry plantations from Inácio (2009), Pulrolnik et al. (2009) and Rangel and Silva (2007).

The model workflow can be summarized as follows (Fig. 1): First, crop yields were simulated by MONICA based on local weather conditions and soil properties for all available crop management options. Second, simulated crop yields were fed into CANDY, which simulated the microbially produce N_2O in the soil. Third, the outputs of MONICA and CANDY were integrated into MPMAS together with greenhouse balances, farm characteristics, market prices, and policy conditions. MPMAS then simulated land use, farm income, and greenhouse gas emissions for each model agent over multiple simulation periods and model repetitions.

3.4. *Simulation experiments*

Two sets of scenarios were designed to assess the contribution of ABC Integration credit in increasing the adoption of low emission land-use practices: a baseline scenario [ABC] with all model agents having access to ABC Integration credit (although they might decide not to take it) and a counterfactual scenario [NO_ABC] where no subsidized credit was made available to the model agents. In addition, a number of policy scenarios were formulated to test alternative financing implementations of the ABC program:

- "Less Subsidy" [LESS] increased the credit interest rate by one percent;

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[2] Software and model documentation including the R scripts, input and output files used in this study can be downloaded from the MPMAS developer website https://www.uni-hohenheim.de/mas/software/BrazilGhgSupplement.7z

[3] In other words, each model agent in MPMAS simulates the decision-making of one real-world farm holding. We excluded very small farm holdings because of limited data availability.

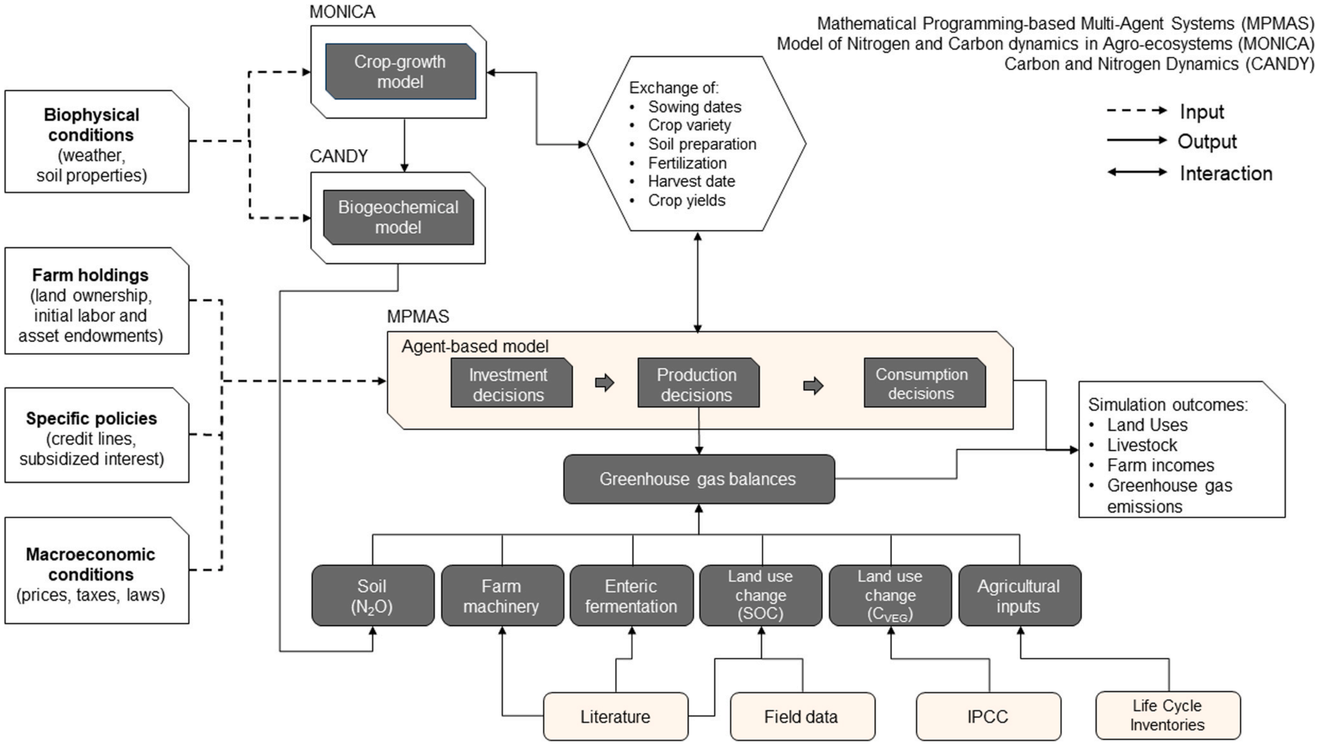

Fig. 1. Model components and data sources used.

- "Own Capital 50%" [OC50] reduced the own capital requirement (i.e. down payment share) to 50%;
- "Own Capital 25%" [OC25] reduced the own capital requirement to 25%;
- "Maximum Amount" [MAX] increased the maximum amount that model agents could borrow by one million BRL.

Note that agent decisions on credit uptake in MPMAS were driven solely by financial considerations. Agents sought to maximize expected farm income and included all available credit sources and credit conditions in their optimal investment and production plan. During the first years of their implementation in Brazil, subsidized ABC credit lines had an annual interest rate of 5% (while the Brazilian Central Bank interest rate was 12%) and own-capital requirements of 65% for forestry and 60% for integrated systems. The maximum loan amount per farm totaled three million BRL for forestry and two million BRL for integrated systems. In all cases where ABC credit increased expected farm income, model agents used this credit line to adopt integrated systems on their farm to the extent technically possible.

The baseline scenario, therefore, reflected an ideal situation of ABC Integration credit without any bureaucratic and social barriers (Gil et al., 2015). The baseline simulation results will therefore most likely overestimate the area of integrated systems in Mato Grosso; they represent an upper limit of adoption had these barriers been removed. We constructed this ideal baseline because no inventories of integrated systems or exact records of on-farm credit usage were available. Nonetheless, farmers' economic incentives and their relative choice between alternative land-use activities, i.e. the policy potential of the ABC credit program in promoting the adoption of integrated systems, should have been well captured in our simulation model. Indeed, the recent survey estimate of EMBRAPA (2016) of 1.5 million hectares with integrated systems in Mato Grosso suggests that our baseline simulation was not too far away in its predictions (see Fig. 3 in Section 4.1).

3.5. *Uncertainty analysis*

In addition to introducing GHG balances, this study also improved on the point estimates for ABC adoption simulated in Carauta et al. (2017) by carrying out an extensive uncertainty analysis using high-performance computing to evaluate the robustness of results. We identified 19 main uncertain parameters in our modeling approach, which can be grouped into five categories: crop yields, selling prices, input prices, emission factors, and synergy effects for integrated systems. Crop yields, as well as selling prices and input prices were highly correlated. To maintain this correlation in our simulation experiments, we did not sample yields and prices independently, but randomly assigned one of six available years with observations (2012–2017) to each repetition and used the complete set of yields and prices from that year in the respective model run. Local prices were corrected for inflation and market trends.

Following the uncertainty testing approach developed by Troost and Berger (2015) and Berger et al. (2017), we applied the Sobol' sequence sampling method, a quasi-random sampling that tends to converge fast and generates samples more uniformly (Tarantola et al., 2012). In order to create a fully controlled experiment that isolates the scenario effect on each individual agent from any variation in other parameters, we ran our simulations over 60 repetitions, and each scenario was simulated using the same Sobol' sequence of parameters. When testing for model convergence, we determined that 60 repetitions were sufficient to make the mean and the 5th and 95th percentile of the simulated GHG reduction converge to a stable value. When comparing simulated land uses with observed land uses of 2011/2012, model efficiency based on standardized absolute errors (ESAE)[4] had values of up to 0.89 for the IMEA sites (for more detailed model validation, see the Supplementary material).

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[4] Troost and Berger (2015) used this indicator for model validation: a value close to 1 indicates almost perfect model fit, and a value less than 0 indicates a fit worse than random allocation.

4. Results

To isolate the direct effects of policy intervention, all simulation experiments were repeatedly run for 3 agricultural years (i.e., the number of simulated cases per scenario was 844 agents * 60 Sobol' repetitions * 3 periods). Land ownership of model agents was fixed by not allowing for land sales and changes in long-term rental contracts. Still, model agents could temporarily rent in or rent out farm land for the duration of one year. Our simulation experiments thus captured the short- to mid-term effects of policy intervention on croplands undisturbed by long-term dynamics on land markets.

4.1. *Adoption of integrated systems*

Fig. 2 depicts the simulated adoption of integrated systems for each agent averaged over all repetitions and simulation periods. Agents are ranked by farm size without ABC credit; 59% of the agent population increased their integrated systems area, leading to a positive change on average. The larger the incidence and average size of the adopted area, then the larger the farm size. Below 500 ha, there was virtually no adoption among agents, and only very few cases between 500 and 1000 ha (as later discussed in Fig. 8 of Section 5.1). Comparing the baseline and counterfactual scenarios pairwise for each agent in all years and repetitions yielded 11% incidence of cases where agents took up ABC credit and increased their individual area with integrated systems (the intended policy outcome). In 6% of all simulated cases, however, agents took up ABC credit and only maintained or even decreased their integrated systems areas. In other words, our model uncertainty analysis revealed a substantial incidence of non-intended versus intended policy outcomes. In the remaining 83% of simulated cases, agents did not take up any ABC Integration credit.

Fig. 3 upscales the simulation results to the whole of Mato Grosso for the alternative policy financing scenarios, with box plots indicating the model uncertainty over all agents and repetitions. The simulation experiments confirmed the policy assessment in Carauta et al. (2017), although showing a somewhat smaller median aggregate agent response to ABC Integration credit than the point estimates. As in the 2017 study, lowering the own-capital requirements when financing integrated systems leads to larger area adoption among agents.

4.2. *Primary greenhouse gas emissions*

Fig. 4 shows the simulated primary emissions for the various crop, livestock, and forestry systems per hectare and year. Primary emissions are calculated by summing all sources of direct emissions from agricultural inputs, enteric fermentation, machinery production, diesel combustion, and microbiological processes (nitrification and denitrification). Therefore, the emission box plots refer to cultivation practices only; computing the net carbon effect (Strey et al., 2016) through ABC credit requires adding possible changes of carbon stocks above and below ground (discussed in Sections 4.3 and 4.4).

For crop activities, primary emissions (Fig. 4) from cotton cultivation are significantly higher than in soybean and maize because of the intensive use of chemical inputs and machinery. The large variation of GHG emissions in livestock is related to key management variables such as pasture type, fertilizer application, length of production cycle, and herd composition. Cattle fattening implies higher primary emissions than breeding and full-cycle production given its higher stocking rates. Forestry plantations, in contrast, have very low direct emissions.

4.3. *Above- and below-ground carbon stocks*

Since atmospheric CO_2 can be stored as carbon in vegetation and soils, land-use change results in either carbon sequestration or carbon release. As Schielein and Börner (2018) pointed out, deforestation in the Amazon and Cerrado biomes of Mato Grosso was influenced by different drivers over the past decades, and processes of land-use change usually moved from native vegetation to pasture and then from pasture to

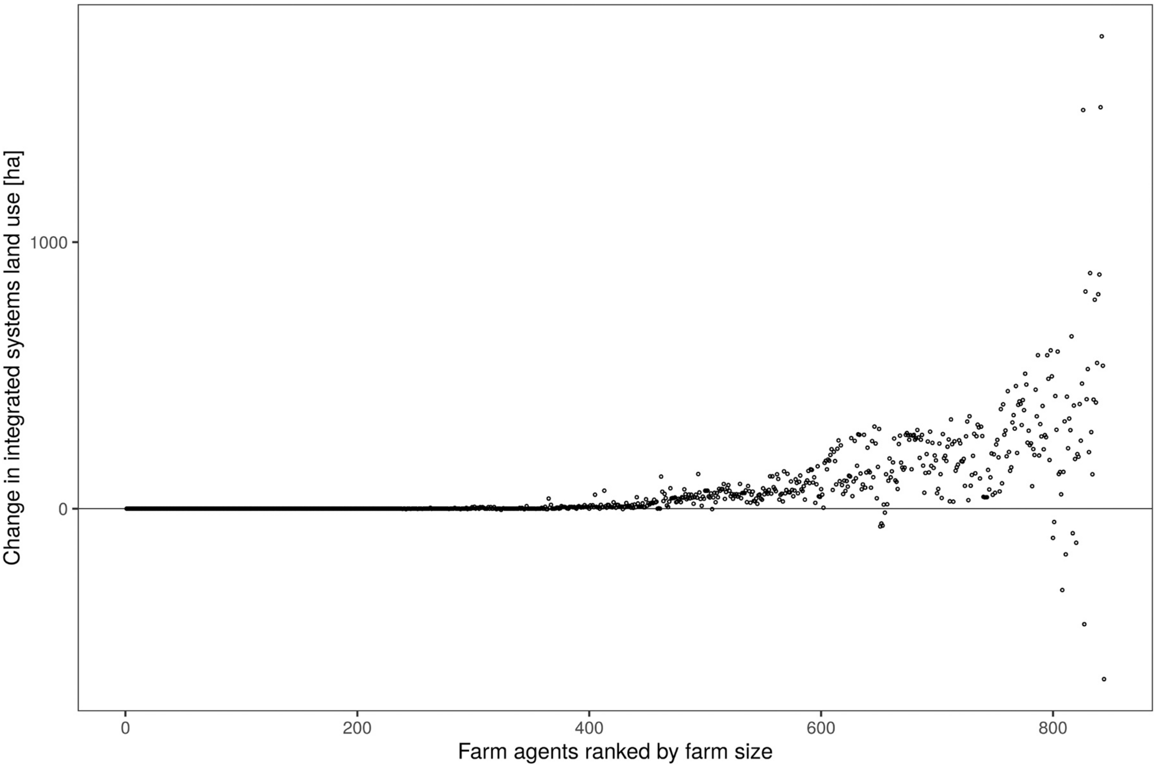

Fig. 2. Simulated adoption of integrated systems for each farm agent, indicating individual areas averaged over repetitions and simulation periods in baseline [ABC] versus counterfactual [NO_ABC] scenarios.

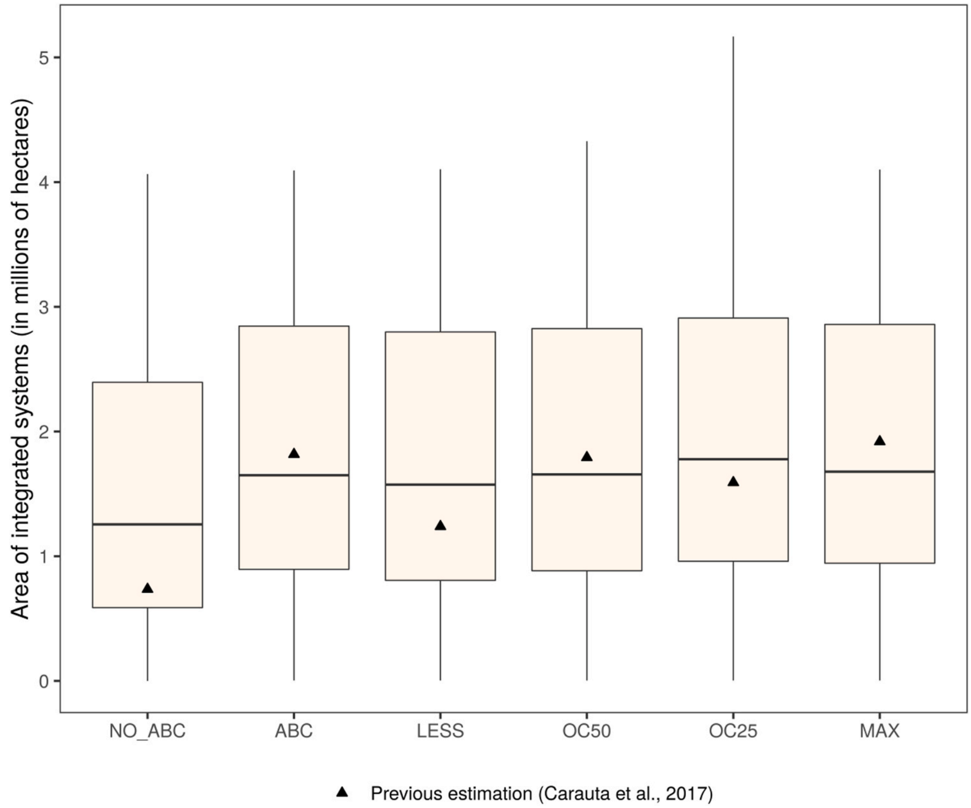

Fig. 3. Simulated areas with integrated systems on cropland farms, upscaled to Mato Grosso using IBGE sampling weights. Scenarios: baseline [ABC], counterfactual [NO_ABC], less subsidy [LESS], own capital 50% [OC50], own capital 25% [OC25], and maximum amount [MAX].

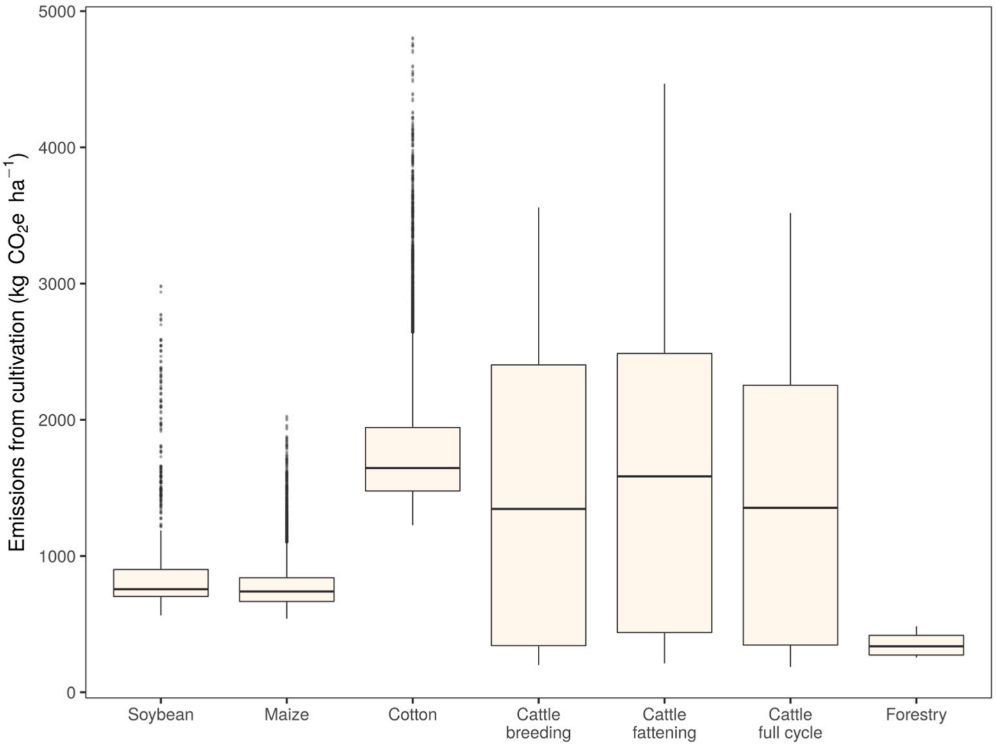

Fig. 4. Simulated primary GHG emissions for agricultural production systems in Mato Grosso, indicating direct emissions from cultivation (without changes in carbon stocks above and below ground).

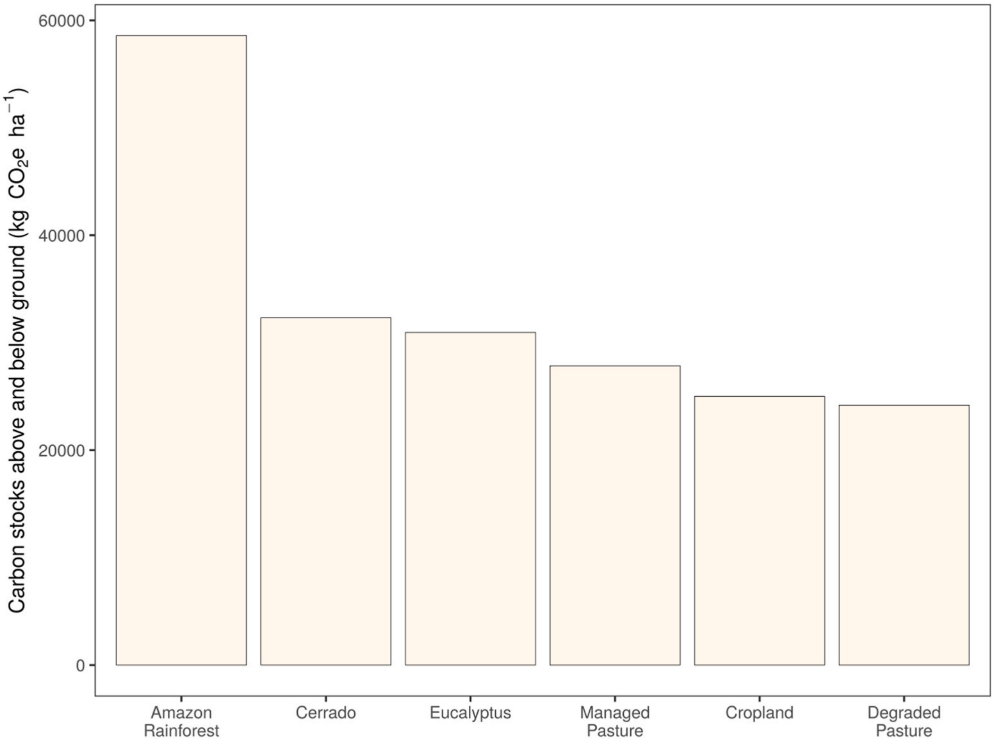

Fig. 5. Simulated average carbon stocks above and below ground.

cropland. Fig. 5 depicts the simulated carbon stocks above and below ground: Native vegetation (Amazon rainforest and Cerrado) and Eucalyptus plantations accumulate more carbon above and below ground than cropland or pasture. Managed pasture displays a larger stock of carbon than degraded pasture or cropland.

For agent policy responses that imply a change in land use from annual cropping to forestry plantation, the net carbon effect is clearly positive (less emissions per hectare through cultivation practices plus additional carbon sequestration above and below ground). When agents, however, adopt integrated livestock systems, the net effect highly depends on the exact livestock and grazing system (i.e., stocking rate, forage type, and specific management practice). Among the simulated cattle production systems (Fig. 6), full-cycle systems showed – in all three pasture intensity levels – slightly lower per-hectare GHG emissions

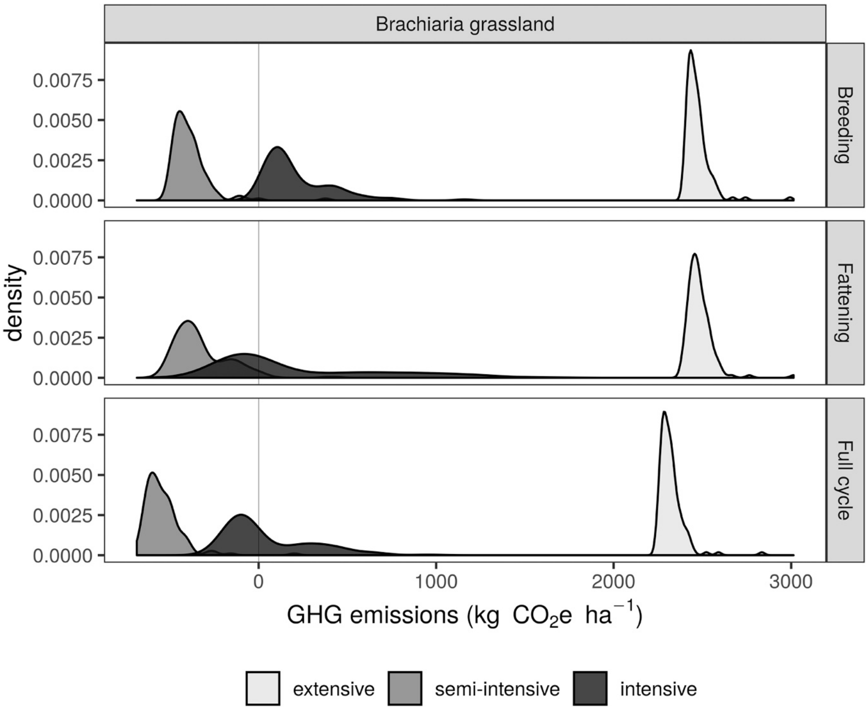

Fig. 6. Simulated GHG emissions for cattle production systems in Mato Grosso, with changes in carbon stocks above and below ground (cropland as previous land use). Note that these results are preliminary due to current scarcity of experimental data.

than pure breeding and fattening. Due to poor grazing management, which retains lower carbon stocks, cattle production on extensively used, degraded pastures shows much higher net emissions than cattle production on semi-intensive and intensive pastures. Note, however, that only few data points were available for semi-intensive and intensive pastures; the simulated difference between these two must therefore be considered preliminary (intensive pastures are expected to have larger carbon stocks, which would then result in a more favorable GHG emissions balance).

4.4. Net emissions upscaled to state level

Fig. 7 shows the distribution of the simulated total change in GHG emissions due to ABC credit, reflecting the combined uncertainty in simulated ABC adoption and GHG balances of agent land use activities. Simulated changes in GHG emissions are calculated by comparing the baseline scenario [ABC] with the counterfactual scenario [NO_ABC] in each of the 60 Sobol' repetitions in our quasi-random uncertainty sample. Due to the model uncertainties involved, the simulated net GHG emission effects of the ABC credit program spread over a large range from −1.07 to 0.23 million tons of CO_2e. While the sample median shows a slight emission reduction of 0.17 million tons of CO_2e, an increase of total emissions was simulated in a non-negligible number of cases.

5. Discussion

The ABC Credit Program has been the main credit line available to farmers in Mato Grosso to finance the goals and technologies advocated by Brazil's Low-Carbon Agriculture Plan. Since its introduction in 2010, however, the ABC Credit Program never achieved its projected potential, reporting slow credit uptake over the years. Earlier program assessments relied upon the observed supply of credit—as in Observatório ABC (2016)—and/or average effects of interventions—as in Lima and Gurgel (2017) and Observatório ABC (2017), but neglected the heterogeneity of farmer responses and possibility of deadweight losses due to average gains from other farmers.

5.1. Implications for policy uptake

Carauta et al. (2017) conclude in their simulation assessment that, despite slow uptake, the ABC Integration credit indeed stimulated the adoption of integrated agricultural practices in Mato Grosso and that suggested modifications of the credit scheme would likely only minimally increase adoption. The explicit model uncertainty analysis conducted in this study confirms this earlier result and shows that the general pattern is robust against fluctuations in product and sales prices and other modeling uncertainties. It also shows that the point estimate of Carauta et al. (2017) for the ABC credit effect is above the median but within the interquartile range of the simulated uncertainty range.

Related to the first major finding of this study, our model uncertainty analysis suggests a large incidence of simulated cases where ABC Integration credit was insufficiently attractive for farm agents to be taken up. Compared to the intended policy outcome, this approach also revealed a substantial incidence of simulated cases where credit uptake by agents did not increase the area of integrated systems. We interpret this as an indication for deadweight policy losses. Non-adoption of ABC credit was especially pronounced among agents below 1000 ha of cropland; virtually no adoption took place below 500 ha. This is because model agents with small cropland areas did not take ABC credit. Rather, they met their cash requirements using other official credit lines with similar interest rates but without any climate-motivated conditions, the so-called *custeio agrícola* (CA) credit for operational expenditures. Note that the microeconomic principles implemented in our simulation models make agents prefer financing means with fewer "strings" attached, just as in reality where farmers will quickly abandon unprofitable production or financing options if better alternatives are available. As CA credit has an upper limit of 1 million BRL per farm, it is of only limited use for larger farm holdings.

To illustrate the importance of this competition between various

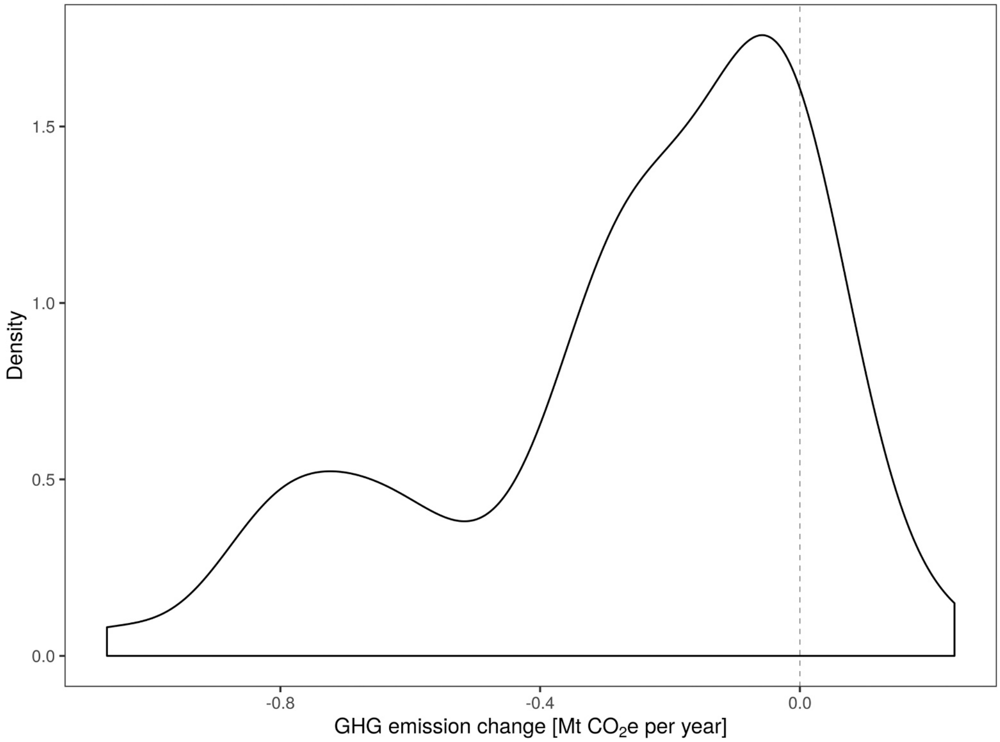

Fig. 7. Simulated change in GHG emissions on cropland farms comparing the baseline [ABC] with the counterfactual scenario [NO_ABC], upscaled to Mato Grosso using IBGE sampling weights.

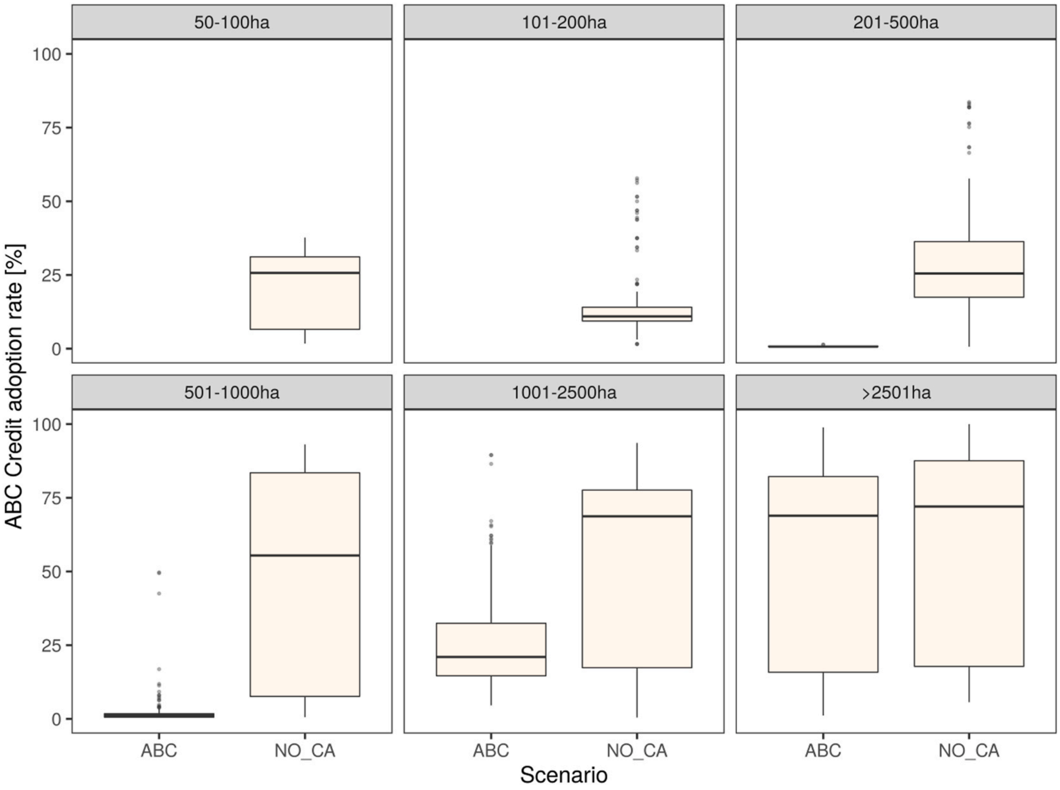

Fig. 8. Simulated adoption of ABC credit comparing the scenarios baseline [ABC] and without custeio agrícola [NO_CA]. Note: ABC credit adoption rates refer to the share of adopters in each farm size category over all Sobol' repetitions.

financial instruments, we simulated an additional counterfactual scenario lacking the CA scheme for operational expenditures. Fig. 8 shows that in this hypothetical scenario [NO_CA] the uptake of ABC credit among model agents increased strongly up to farm sizes of 2500 ha, and the total area of integrated systems increased by 53% to 2.5 million hectares in the median of the uncertainty sample when compared to the [ABC] scenario. Of course, it may be questioned whether dropping a fundamental and established credit scheme such as CA in favor of a green financing scheme such as ABC is politically feasible and socially desirable. Still, our findings underline that the ABC credit scheme has to be considered in competition with other existing means of financing.

5.2. Implications for policy effectiveness

A second major finding involves our assessment of the GHG effect of adopting integrated systems on croplands in Mato Grosso incentivized by ABC credit. The production-specific emission balances that we simulated suggest that those agent policy responses implying a change in land use from annual cropping to forestry plantation lead to a net reduction in carbon emissions (fewer emissions per hectare from cultivation practices plus additional carbon sequestration above and below ground). In contrast when agents adopt integrated livestock systems, the net effect highly depends on the specific livestock and grazing system (i.e., stocking rate, forage type, and specific management practice) chosen. When simulating the total GHG effect of ABC adoption, the combined uncertainty in GHG budgeting and the uncertainty in simulating agent decisions resulted in a wide uncertainty band in terms of overall net emissions. This uncertainty band includes large GHG reduction effects but does not rule out maladaptation to the point that overall emissions might even have increased.

5.3. Limitations of this study

Our model parameterization has so far focused on understanding the economic rationality of crop farming, the most important economic land use in Mato Grosso. Due to limited data availability, our current agent population is composed of cropland farms only. This study simulates livestock production as a potential option for these agents to diversify into an integrated production system. We believe that further improving our database and model representation of livestock-related decision-making would substantially reduce the simulated model uncertainty. Moreover, this would also allow us to include the existing cattle farms into our simulation analysis. There are currently about 23 million hectares of grassland in Mato Grosso, of which 7% were declared degraded in the latest agricultural census (IBGE, 2017). According to our simulations, there is great potential to store carbon above and below ground when upgrading grassland from extensive to semi-intensive livestock and agro-forestry systems, which we could not yet consider in our current policy assessment.

6. Conclusions

The present study illustrates that fine-scale simulation analysis employing an agent-based bioeconomic model system can facilitate policy assessment of market-based climate mitigation schemes in agriculture. Our assessment of GHG emissions reduction thereby goes beyond measuring credit uptake and the adoption of incentivized measures at the aggregate level. It allows for counterfactual analysis and an assessment of actual GHG emission effects using available statistical and experimental data for life-cycle assessment. An extensive model uncertainty analysis ensured the robustness of the results and, as in our case, highlighted the knowledge gaps that future policy analysis must address.

The counterfactual simulation of ABC credit uptake and integrated systems expansion underlines three important points: First, the stimulation effect of ABC credit on integrated systems area has certainly been low, but largely positive over the assessed model uncertainty. Second and perhaps inevitably, there are deadweight policy effects where those already practicing a desired activity benefit from the policy intervention at no cost and without change of behavior. Third, our results highlight the limited capacity of smaller farm holdings to absorb loan-based green financing. If less restrictive financing options are already available and sufficient to cover farm liquidity needs, then offering an additional, conditional credit scheme will likely not encourage uptake and altered behavior. This might be different if the incentivized activities were more profitable than current practices but hampered solely by a lack of liquidity. In such a policy setting, for example, direct payments for environmental services could be more effective (see the simulations of Troost et al. (2015) regarding the agri-environment-climate support measures of the European Union). This again underscores the need to consider the full farmer decision context when designing incentive-based policies; those policies may then have to be composed of a mix of measures targeting different farmer groups.

In terms of the overall carbon footprint of ABC Credit, however, we cannot yet present a final policy impact result. The uncertainty range for the total effect on GHG emissions is currently too wide for any serious assessment of the cost effectiveness or even cost-efficiency of the measure. Moreover, our uncertainty assessment reveals that even an adverse effect on GHG emissions cannot be ruled out completely. Work is ongoing to enrich the parameterization of the livestock model component to address this issue and complete the computation of net carbon effects, including also grasslands.

Nonetheless, the Brazilian case already offers important lessons for other land-rich countries that build their climate mitigation policies on economic incentives. Clearly, farmer policy responses should be more thoroughly analyzed using ex ante assessment methods and before implementing nation-wide green financing programs. Moreover, incentives should be directly linked to the target variable GHG emissions and not to intermediate variables such as areas of integrated systems. Our analysis did not address the interplay between processes of land conversion from forest to pasture to cropland. We believe, however, that incentive-based policy programs in agriculture can only be effective in the longer run if they are accompanied by robust forest law enforcement as highlighted in Tacconi et al. (2019). Otherwise, “frontier expansion” into native forest will not, as suggested by Stabile et al. (2020), be replaced by sustainable agricultural intensification. Instead, deforestation rates will further explode, threatening Amazonia’s environment, traditional peoples, and the global climate (Ferrante and Fearnside, 2019).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2021.105618.

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