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Assessment of Policies for Low-Carbon Agriculture by means of Multi-Agent Simulation

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Abstract: Agriculture and agriculture-inflicted land use change is a major source of greenhouse gas (GHG) emissions. Reducing excessive deforestation and intensification of agricultural land use and consequently reducing associated GHG emissions is an important pathway of transition to a global low-carbon economy. Adoption of low-carbon agricultural systems and practices requires setting appropriate economic incentives for land users through smart policy instruments. For effective implementation of such instruments integrated ex-ante policy assessments are crucial. In this article we discuss and illustrate the benefits and potentials of applying multi-agent system models for the assessment of low-carbon policies and technologies. As an empirical example we discuss the use of the software package MPMAS that we are currently deploying for the assessment of impacts of low-carbon technologies and policies in the Southern part of Brazilian Amazon. Our agent-based application implements one-to-one correspondence between real-world farms and computational agents and is able to realize spatially explicit simulations of farm behavior. MPMAS is externally coupled with the dynamic, process-based crop growth model MONICA hereby interlinking economic behavior of farms with processes of carbon, nitrogen and water turnover. The values of GHG emissions are simulated by the biochemistry model DNDC, which was calibrated *in situ* based on empirical measurements. Our application has a graphical GIS-interface that can inform policy evaluators about simulated results.

Keywords: agent-based modeling, low-carbon agricultural policies, land-use and land-cover change, life-cycle assessment, Brazilian Amazon

1 INTRODUCTION

According to IPCC (2007), agriculture and forestry contribute 30.9% of total anthropogenic GHG emissions on the planet, while agriculture alone is being responsible for 13.5 % of the emissions. With the increasing demands for food, caused by population and income growth, the amount of emissions originating from land use, land-use change and forestry (LULUCF) is expected to further increase (IPCC, 2007). One of the large emitters of GHG from LULUCF is Brazil, where more than two thirds of the country emissions are inflicted by these sources (Cerri et al., 2007)

Brazil's rapidly advancing agricultural frontier and emission hot spot is located in the State of Mato Grosso (MT) (Galford et al., 2011). Gradual clearing of forest and savannah vegetation for pasture and cropland there, together with the intensification of agriculture, results in roughly one percent of annual global GHG emissions (IPCC, 2007). A likely further expansion of the soy bean – maize double cropping system in the State may lead to increased conversion of natural vegetation to cropland and to coupled GHG emissions from agriculture, for example N_2O from fertilizer application and CO_2 from soil tillage (de Espindola et al., 2012). To slow down this process several policy instruments are being applied in MT such as projects of the U.N. framework of Reducing Emissions from Deforestation and Degradation (REDD), promotion of integrated production systems, etc. (Börner and Wunder, 2012; Galford et al., 2013; Nepstad et al., 2013).

In order to design a suitable portfolio of policy instruments aiming at GHG reduction, which means offering viable low-carbon strategies for land management, conduction of ex ante economic assessments is important. From our point of view, it is important to conduct such analyses at the farm-level, because making the strategies work implies that farmers actually adopt them. Whole-farm modeling is therefore needed to investigate the incentives and barriers for adoption of various strategies. Effective strategy design and policy targeting requires accounting for site-specific production conditions of different farms (i.e. natural factors, resource endowments, market linkages, etc.). In this respect multi-agent system models of land-use/cover change (MAS/LUCC models) are particularly useful, since they are capable to reflect the heterogeneity of land users and their incentives for adoption (Berger et al., 2006).

In this paper we present an empirical application of the agent-based software MPMAS (Schreinemachers and Berger, 2011) for the assessment of policies targeting at the reduction of GHG from LULUCF. We discuss its integration with biochemistry simulation models and describe the various use cases which we are currently elaborating in Brazil.

2 RESEARCH SETTING

This research is done as part of the interdisciplinary project "Carbiocial – Carbon-optimized land management strategies for Southern Amazonia" (www.carbiocial.de). The project assesses land management strategies that could decrease anthropogenic GHG emissions in the Southern Amazon and maintain ecosystem services provided. The project collaborators do so by taking into account changing climate conditions and ongoing economic transformation of the region. The project integrates researchers from various related disciplines, such as agronomy, geography, environmental sciences, agricultural economics and social sciences, thus creating a foundation for holistic and multi-perspective analysis of the studied bio-economic systems.

2.1 Study Area

The study area of our research comprises five macro-regions of the State of MT (classification of IMEA (2014)): mid-North, North East, South East, Central South and West. The selected regions extend over about two thirds of the State's territory with most of the State's agricultural output being produced in these regions (IMEA, 2014).

MT is the third largest state of Brazil by area occupying 903,366 km^2. (IBGE, 2014). In the last decades, the State experienced a continuous intensification and expansion of agricultural activities. According to IBGE (2014), in 2010 MT accounted for 27.3% of the national soybean production, for 14.5% of the national maize production and for 49.3% of the national cotton production. In 2009, 13.3% of the Brazilian cattle population was residing in the State. Figure 1 shows the dynamics of annual crop production in MT in terms of the planted area (data of IBGE (2014)) and Figure 2 shows the dynamics of local livestock population (data of IBGE (2014)).

Figure 1: Cropland in MT

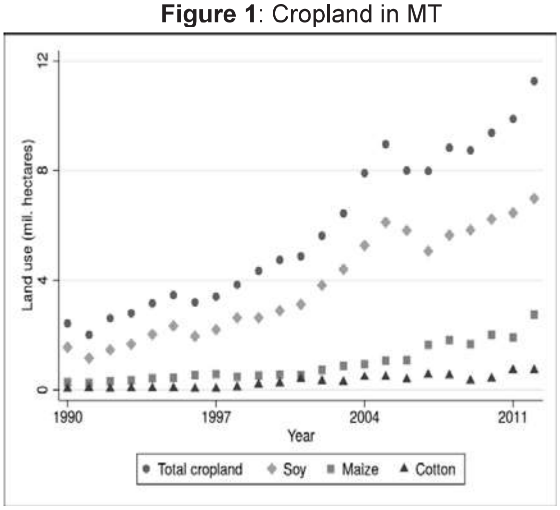
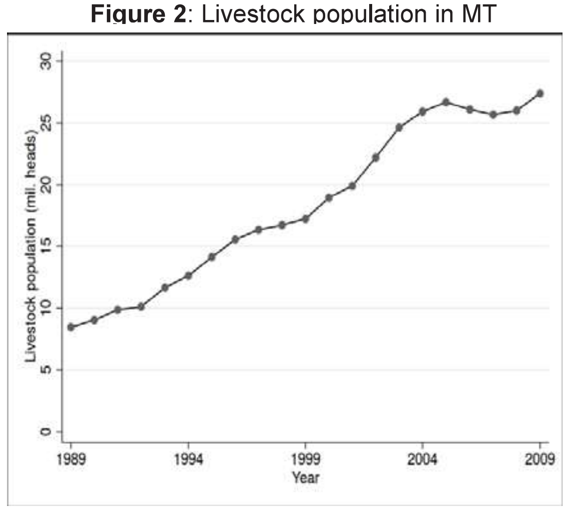


Figure 2: Livestock population in MT



In 2004, the deforestation rates in MT were around 12,000 km^2 per year (INPE, 2014). Deforestation significantly decreased since then to around 1,000 km^2 in 2013 (INPE, 2014), but still land clearing and subsequent soil tillage release large amounts of GHG (Galford et al., 2011).

3 MODEL DESCRIPTION

In our research we integrate three simulation models: the socioeconomic agent-based model MPMAS and two process-based biochemistry models, MONICA and DNDC. This section of the paper provides a description of the models.

3.1 MPMAS

Mathematical Programming-based Multi-Agent Systems (MPMAS) (Schreinemachers and Berger, 2011) is a simulation package for dynamic modeling of agricultural holdings. It is based on the integration of an agent-based module representing the activity of land users with a cellular module representing a geographical landscape. MPMAS employs mathematical programming to model the production, investment and consumption decisions of farm agents. As shown in equation (1), agents in MPMAS maximize expected utility by choosing the optimal land use and resource allocation and accounting for individual risk aversion. The software simulates the multi-period dynamics by implementing the temporal carry-over of agent resources and updating of agent expectations. Also, MPMAS is programmed such that it allows coupling with external crop growth models through crop yields (explained in Section 4.1)

$$\begin{cases} \mathrm{Max!\,U = E - 0.5 * r * Var(E)} \\ \mathrm{E = R_c + R_l + R_f + R_p - V - F} \end{cases} \tag{1}$$

where *U* – expected utility; *E* – expected income; *Var(E)* –income variance;
r – risk aversion coefficient;
$R_{c,\,l,\,f}$ – revenue from crop and livestock production and forestry;
R_p – revenue from policies; *V* – variable costs; *F* – fixed costs

The empirical applications of MPMAS (see overview in Schreinemachers and Berger (2011)) are aimed at conduction of scenario-based analyses to identify and understand the effects of technological, environmental, policy changes and interventions on the studied population of farms and the related resource pools. Parameterization of the applications is based on implementing the one-to-one correspondence between model agents and their real-world prototypes (farms).

For the application presented in this paper, we consider all existing farms in the study area that have 50 or more hectares of land under their operation as the reference population. Information on the number of farms in the study area was taken from the IBGE (2014) online database. Sizes of farm land holdings and available machinery were also calculated from IBGE (2014). For the definition of crop and livestock production alternatives for our application we used publicly available farm data of IMEA (2014), Agrianual (2014) and Anualpec (2014). Information on soils was taken from the geo-referenced soil database of Brazil (Muniz et al., 2011). Prices for agricultural produce and inputs were taken from IMEA (2014). Remaining gaps in required data were filled using expert opinion.

3.2 MONICA

The Model for Nitrogen and Carbon in Agro-ecosystems (MONICA) is a successor and a fundamentally revised version of the HERMES agro-ecosystem model (Kersebaum, 2007). The MONICA model is a simulator of nitrogen and carbon turnover in agricultural systems, which can be applied for modeling climate change impacts on crop growth (Nendel et al., 2011).

In this research MONICA is used for the simulation of crop yields of different crop production alternatives relevant for the study area. The model simulates crop yields for particular soil types and climate conditions. MONICA simulations also capture the yield effects of choosing different seed varieties, planting dates and fertilization practices. The adaptation of the MONICA model for the study area conditions is done by its developer C. Nendel from Leibniz Centre for Agricultural Landscape Research (ZALF) as part of the Carbiocial Project.

3.3 DNDC

DeNitrification-DeComposition (DNDC) is a computer simulation model focusing on carbon and nitrogen. It is a particularly suitable for modeling trace gas emissions from agricultural systems (Giltrap et al., 2010; Li, 2007), e.g. CO_2, N_2O, CH_4, NO, NH_3 and N_2. After its initial development by Li, (1992), the DNDC model was extended and adapted for modeling various production systems (Giltrap et al., 2010).

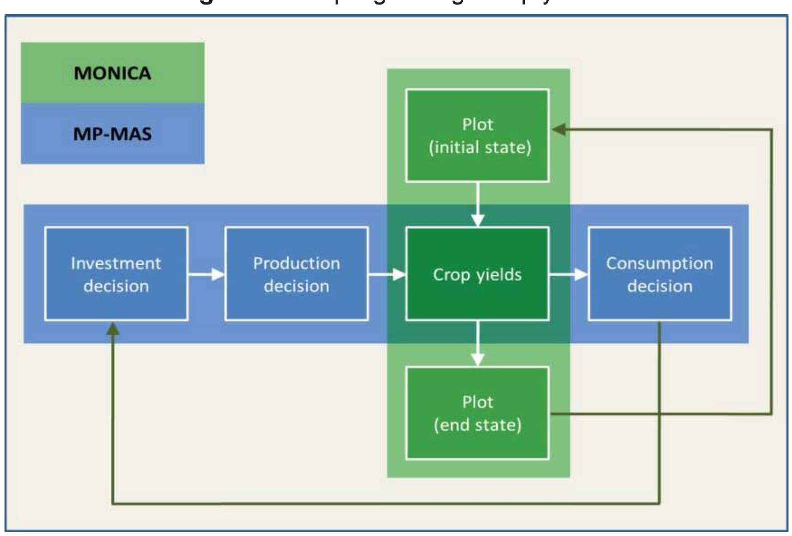
In our research DNDC is used to simulate the emissions of GHG of different LULUCF activities (The approach that DNDC follows when modeling GHG emissions from soils is described in Li (2007).) The model is currently being calibrated for the study area conditions by K. Meurer from the Helmholtz Centre for Environmental Research (UFZ) based on empirical measurements in MT.

4 MODEL INTEGRATION

4.1 MPMAS – MONICA coupling

As part of the Carbiocial Project, a run-time coupling of MPMAS and MONICA has been developed. In the coupled system, models interact with each other through land use and crop yields (Figure 3). First, MPMAS produces agent farm plans using expected yields. Then, it sends these land use plans to MONICA, which simulates the respective crop yields, based on the site-specific soil and climate conditions. Based on the actual yields produced by MONICA, MPMAS calculates the results of economic performance of farm agents and implements the carry-over of agent assets to the next agricultural year. In this way, recursive-dynamic simulation runs can be performed over a multi-year period.

Figure 3: Coupling through crop yields

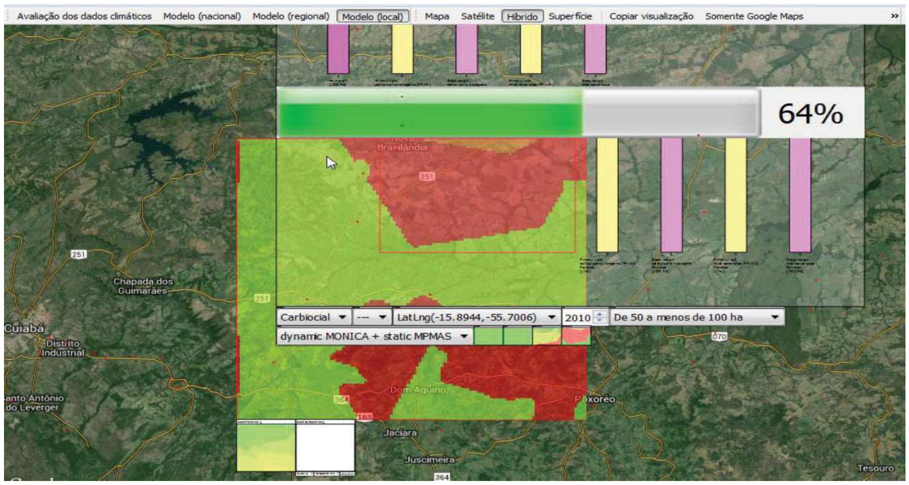


A consistent integration is achieved by using a shared SQL database containing data on crop production alternatives for MPMAS and MONICA.

4.2 Decision-support system

The coupled model system has a graphical user interface (GUI) containing soil maps (based on Muniz et al., 2011) and historical climate data from local meteorological stations. Also, it is synchronized with Google Maps® and can display terrain and road maps from Google Maps®. The GUI was originally developed by Wenkel et al. (2013) in ZALF. It was later adapted by the ZALF team for the Carbiocial study area and extended to include the results of farm performance simulated by MPMAS.

Figure 4: Decision-support system. Screenshot



The GUI has been designed to support the decisions of local land users. Through the interface its users can apply the MPMAS – MONICA system for improvement of farm planning. The user selects the location and the size of the farm, for which he or she wants to perform computations, and the interface displays the results of respective model computations. The GUI provides visualized information on simulated optimal land use, crop yields, per hectare gross margins of different land use activities and total profit of the farms.

4.3 Integration of GHG-emissions

The DNDC model is not run-time coupled with MPMAS and MONICA. Instead, it is used to pre-calculate the emission balances of the LULUCF alternatives implemented in the MPMAS agent decision module. Simulated total annual emissions of various GHG (i.e., the results of DNDC computations) of these alternatives are recorded in the SQL database. MPMAS accesses this database to include the emissions of GHG from LULUCF activities in the whole-farm modeling.

GHG emissions associated with the use, production and transportation of agricultural inputs and machinery as well as emissions from cattle are estimated based on NREL (2014) and GaBi (2014) databases.

5 USE CASES AND EXPECTED RESULTS

Currently, we are working on the elaboration of model use cases of our software application. These use cases are aimed at delivering high-resolution quantitative data for land users and policy makers concerning the policy measures stimulating mitigation of GHG emissions from LULUCF. In this section we describe three identified model use cases and discuss their implementation in practice.

5.1 Farmer cost of GHG mitigation

In this model use case, we are testing several technology options for mitigating GHG emissions from agriculture in MT. The most recent innovation in the study area related to low-carbon agriculture is integrated crop-livestock systems. These novel systems are promoted by the national research organization EMBRAPA and consist of putting cattle to soy fields in off-season. They are likely to decrease GHG emissions through low-carbon balances and prevention of further land degradation.

Other technologies to be tested include rehabilitation of degraded pastures (described by Cerri et al. (2005)) and various practices of conservation agriculture (discussed in Galford et al., 2013), which can also potentially reduce incentives for deforestation.

Prospective simulation experiments will estimate the opportunity costs of farmers in study area for adopting the discussed low-carbon strategies. The results of our simulation experiments within this use case will inform about the distribution of costs of mitigating one ton of GHG emissions in CO_2 equivalent among the modeled farms. Our task is now to collect more precise technical information with regard to the costs of adopting the various innovations on-farm and to introduce these technologies as alternatives for the farm agents in MPMAS.

5.2 Effect of national policies (ABC Program) on GHG mitigation

In continuation to the commitments that the Brazilian federal government made during the U.N. Climate Change Conference (COP15) in 2009, it launched a national plan of promoting low-carbon agriculture (ABC Plan) together with a special line of credit (ABC Program). The goal of the ABC Program is stimulating the adoption of sustainable low-carbon agricultural practices, such as no-tillage farming, biological nitrogen fixation and integrated crop-livestock-forestry systems (BNDES, 2014). For implementation of these practices on–farm, the program offers preferential loans to agricultural producers.

After implementation of low-carbon production alternatives in the agent decision module (previous use case), we will assess the impacts of the ABC Program (in the set-up as it is currently offered) in order to estimate the social cost of GHG mitigation per ton of CO_2 equivalent. In addition, we will test alternative set-ups of the program and investigate the potential for improvement.

5.3 Potential effects of REDD+ projects

Brazil is currently working on the formulation and implementation of domestic REDD+ strategies – both at the national and the federal state level. The government of MT for instance, is now developing a REDD-supportive legal framework.

Our coupled model system can also be used for the cost-effectiveness assessment of prospective REDD projects (e.g. afforestation and reforestation, maintenance of legal forest reserves on the farms) as well as for the identification of locations where REDD projects might have higher chances of running successfully. The simulation results can then also improve and support the design of compensation and certification mechanisms for farmers.

6 CONCLUSIONS AND OUTLOOK

In this paper we discussed the development of a coupled multi-agent system for simulating LULUCF and assessing the effects of policy interventions and low-carbon technologies. We identified three use cases for the model system and outlined their expected results. Currently, we are working on the parameterization of simulation scenarios for the various use cases.

There are certain advantages that the described model implementation has in comparison to aggregate sector or regional simulation models. First, the agent-based specification of the simulation model allows reflecting the real-world heterogeneity of land users, the diversity of the bio-economic conditions and the economic incentives they are facing. In addition, implementing the temporal carry-over of farm assets and modeling agent investment decisions provides an opportunity to conduct farm-level assessments of policy effects in the long-run. Second, basing the biochemistry components of the system (MONICA and DNDC) on empirical observations from the study area improves the spatial validity of model results. Third, the effects of low-carbon agricultural technologies in terms of their requirements for farm resources such as machinery, labor or financial capital, can be captured. Finally, the simulation results produced for individual farms can be directly interpreted by local stakeholders, which together with the developed graphical user interface will serve for a better dissemination of research results.

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