UNIVERSITY OF HOHENHEIM

Faculty of Agricultural Sciences

Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute)

Department of Land Use Economics in the Tropics and Subtropics (Josef G. Knoll Professorship)

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Assessing alternative options to improve farming systems and to promote the adoption of low-carbon agriculture in Mato Grosso, Brazil

Dissertation

submitted in fulfillment of the regulations to acquire the degree "Doktor der Agrarwissenschaften" (Dr.sc.agr. in Agricultural Sciences) to the Faculty of Agricultural Sciences

presented by

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Rio de Janeiro, Brazil

2018

This thesis was accepted as a doctoral thesis (Dissertation) in fulfillment of the regulations to acquire the doctoral degree “Doktor der Agrarwissenschaften” (Dr. sc. agr.) by the Faculty of Agricultural Sciences at University of Hohenheim.

Date of the oral examination: April 08, 2019

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Summary

Currently, our society faces a significant challenge to eradicate hunger and poverty while preserving natural resources and reducing greenhouse gas (GHG) emissions. In this context, Brazil plays an important role since it is one of the most significant players in global food production and hosts a variety of ecosystems and a significant share of the Earth's biodiversity. The federal state of Mato Grosso (MT) is located at the most dynamic agricultural frontier in the *Cerrado-Amazon* transition zone and leads the national production of grain, fiber, and meat.

The need to balance agricultural production and environmental protection shifted the focus of Brazilian land-use policy toward sustainable agriculture. The federal government pledged to reduce its GHG emissions and implemented policies to enforce it. Brazil's low-carbon agricultural plan offers credit with low-interest rate to farmers who want to implement sustainable agriculture practices. These include the restoration of degraded pasture, adoption of integrated systems, no-till agriculture, biological nitrogen fixation, commercial forests, treatment of animal wastes, and climate change adaptation.

The present thesis contributed to the CARBIOCIAL project ("Carbon-optimized land management strategies for southern Amazonia"), a German-Brazilian cooperation to investigate viable carbon-optimized land management strategies maintaining ecosystem services under changing climate conditions in the Southern Amazon. In this context, this thesis examines options to improve farming systems in MT and evaluates policy measures that could promote the adoption of low-carbon agricultural systems.

The work is divided into three parts: The first part is subdivided into three chapters (chapters 1, 2 and 3) and offers an overview on land use change in Brazil and explores land use decisions of farmers in MT, where highly dynamic double-crop systems currently prevail. The second part is subdivided into two chapters (chapters 4 and 5) and is dedicated to evaluating alternative options to improve farming systems in MT. The third part is subdivided into three chapters (chapters 6, 7 and 8) and investigates factors that may influence farmers to adopt IAPS, evaluates policy measures to promote the adoption of low-carbon agricultural systems, and provides a detailed quantification of individual GHG emissions of a large variety of agricultural practices and the aggregate emissions resulting from their current use in MT.

To this end, this thesis develops an Integrated Assessment (IA) approach that simulates farm-level decision-making and agricultural land use change. It introduces a novel approach to evaluate the full distribution of GHG emissions related to the agricultural land-use change in MT. 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). Data to parameterize the model was gathered from several sources, such as field experiments, statistical offices, farm level surveys from private consultancies, life-cycle inventory databases, extension services, expert interviews, and literature.

This thesis presents the first extensive study on crop yield response in MT by simulating yields in response to different climatic conditions, soil types, sowing dates, crop rotation schemes, fertilization amounts, and macro-regions. The simulation results show that biophysical constraints still play a crucial role on yield gaps in MT whereas socio-economic constraints have a slight yield-increasing effect. This thesis further examines alternative ways to improve the farming systems in MT by investigating the role of sunflower adoption in increasing farm income. We have found a substantial potential for sunflower cultivation in MT with positive impacts on both farm and regional level. Additionally, we identified bottlenecks for sunflower diffusion such as the distance from farm gate to processing facility. Regarding Brazilian agricultural policy, we have found that the Brazilian low-carbon agricultural program contributed to the adoption of integrated systems. However, we observed different adoption rates through macro-regions and types of integrated systems. Furthermore, our simulations additionally show that the ABC program also contributed to the adoption of less GHG-emitting practices, but its performance is subjected to agent expectations on prices and yields.

Zusammenfassung

Gegenwärtig steht unsere Gesellschaft vor der großen Herausforderung, Hunger und Armut zu beseitigen und gleichzeitig die natürlichen Ressourcen zu erhalten und die Treibhausgas (THG) -Emissionen zu reduzieren. In diesem Zusammenhang spielt Brasilien eine wichtige Rolle, da es einer der wichtigsten Akteure in der globalen Nahrungsmittelproduktion ist und eine Vielzahl von Ökosystemen und einen bedeutenden Teil der Biodiversität der Erde beherbergt. Der Bundesstaat Mato Grosso (MT) liegt an der dynamischsten landwirtschaftlichen Grenze in der Cerrado-Amazonas-Übergangszone und ist führend in der nationalen Produktion von Getreide, Faserpflanzen und Fleisch.

Die Notwendigkeit, Landwirtschaft und Umweltschutz in Einklang zu bringen, verlagerte den Fokus der brasilianischen Landnutzungspolitik auf eine nachhaltige Landwirtschaft. Die brasilianische Bundesregierung hat zugesagt, ihre THG-Emissionen zu reduzieren und hat Maßnahmen zur Durchsetzung implementiert. Der kohlenstoffarme Agrarplan Brasiliens bietet Landwirten, die eine nachhaltige Landwirtschaft praktizieren möchten, Kredite mit niedrigen Zinsen. Dazu gehören die Wiederherstellung degradierter Weiden, die Einführung integrierter Systeme, die Direktsaat-Landwirtschaft, die biologische Stickstofffixierung, kommerzielles Forstbewirtschaftung die Aufbereitung von Tierabfällen und die Anpassung an den Klimawandel.

Die vorliegende Arbeit trug zum Forschungsprojekt CARBIOCIAL ("Kohlenstoffoptimierte Landmanagementstrategien für Südamazonien") bei, einer deutsch-brasilianischen Kooperation zur Untersuchung von Kohlenstoff-optimierten Landmanagementstrategien zur Erhaltung von Ökosystemleistungen unter sich verändernden Klimabedingungen im südlichen Amazonasgebiet. In diesem Zusammenhang untersucht diese Dissertation Optionen zur Verbesserung der landwirtschaftlichen Systeme in MT und evaluiert politische Maßnahmen, die die Einführung von kohlenstoffarmen landwirtschaftlichen Systemen beschleunigen könnten.

Die Arbeit besteht aus drei Teilen: Der erste Teil gliedert sich in drei Kapitel (Kapitel 2, 3 und 4). Er gibt einen Überblick über Landnutzungsänderungen in Brasilien und untersucht Landnutzungsentscheidungen von Landwirten in MT, wo derzeit hochdynamische Zweikultur-Nutzungssysteme vorherrschen. Der zweite Teil besteht aus zwei Kapiteln (Kapitel 5 und 6) und widmet sich der Bewertung alternativer Optionen zur Verbesserung der landwirtschaftlichen Systeme in MT. Der dritte Teil gliedert sich in drei Kapitel (Kapitel 7, 8

und 9) und untersucht welche Faktoren Landwirte beeinflussen integrierte Anbausysteme anzuwenden, bewertet politische Maßnahmen zur Beschleunigung der Einführung von kohlenstoffarmen Agrarsystemen und, quantifiziert die individuellen Treibhausgasemissionen einer Vielzahl unterschiedlicher landwirtschaftlicher Nutzungssysteme sowie die Gesamtemissionen die sich aus ihrer derzeitigen Verbreitung in MT ergeben.

Zu diesem Zweck wurde in dieser Dissertation ein Integrierter Bewertungsansatz entwickelt, der Entscheidungen auf der Ebene landwirtschaftlicher Betriebe und Landnutzungsänderungen simuliert. Sie führt einen neuen Ansatz zur Quantifizierung der detaillierten Verteilung von Treibhausgasemissionen im Zusammenhang mit landwirtschaftlichen Landnutzungsänderungen in MT ein. Unser Integrierter Bewertungsansatz vereint drei Softwarepakete: MPMAS (auf mathematischer Programmierung basierende Multi-Agenten-Systeme), MONICA (Modell für Stickstoff und Kohlenstoff in Agrarökosystemen) und CANDY (Kohlenstoff- und Stickstoffdynamik). Die Daten zur Parametrisierung des Modells wurden aus verschiedenen Quellen wie Feldversuchen, statistischen Ämtern, Befragungen von privaten Beratungsunternehmen auf Betriebsebene, Bestandsdatenbanken für den Lebenszyklus, Beratungsdiensten, Experteninterviews und Literatur zusammengetragen.

Diese Arbeit beinhaltet die erste umfassende Studie zu Pflanzenerträgen in MT, bei der die Erträge in Abhängikeit von unterschiedliche klimatische Bedingungen, Bodentypen, Aussaatdaten, Fruchtfolgepläne, Düngungsmengen und Makroregionen simuliert werden. Die Simulationsergebnisse zeigen, dass biophysikalische Bedingungen immer noch eine entscheidende Rolle für Ertragslücken in MT spielen, während sozioökonomische Bedingungen einen leichten ertragssteigernden Effekt haben. Außerdem untersucht die Arbeit alternative Möglichkeiten zur Verbesserung der landwirtschaftlichen Systeme in MT. Dazu gehört die Einführung von Sonnenblumen und ihr Effekt auf das landwirtschaftliche Betriebseinkommen. Wir konnten ein beträchtliches Potenzial für den Sonnenblumenanbau in MT feststellen, der positive Auswirkungen sowohl auf betriebs als auch auf regionaler Ebene hat. Zusätzlich konnten wir Engpässe für die Verbreitung der Sonnenblume ausfindig machen, wie die Entfernung vom Hoftor zur Verarbeitungsanlage. Was die brasilianische Agrarpolitik anbelangt, so haben wir herausgefunden, dass das brasilianische kohlenstoffarme Agrarprogramm zur Einführung integrierter Systeme beigetragen hat. Wir beobachteten jedoch unterschiedliche Akzeptanzraten bedingt durch Makroregionen und verschiedenen integrierten Systemen. Darüber hinaus zeigen unsere Simulationen, dass das ABC-Programm auch zur

Einführung von weniger THG-emittierenden Praktiken beigetragen hat, aber der Erfolg des ABC Programms ist abhängig von der Erwartung der Agenten im Bezug auf Preise und Erträge.

List of publications included in the doctoral thesis

Chapter 1 **Carauta, M.**, 2016. Combating deforestation in the Brazilian Amazon: options for national and global governance. International Journal of Agriculture and Environmental Research. 2, 17.

Chapter 2 **Carauta, M.**, Libera, A., Hampf, A., Chen, R., Silveira, J. M., Berger, T., 2017. On-Farm trade-offs for optimal agricultural practices in Mato Grosso, Brazil. Revista de Economia e Agronegócio (*Brazilian Journal of Economy and Agribusiness*). 15, 299–322.

Chapter 4 Hampf, A. C., **Carauta, M.**, Latynskiy, E., Libera, A. A.D., Monteiro, L., Sentelhas, P., Troost, C., Berger, T., Nendel, C., 2018. The biophysical and socio-economic dimension of yield gaps in the southern Amazon – A bio-economic modelling approach. Agricultural Systems. 165, 1–13.

Chapter 6 Dantas, I., **Carauta, M.**, 2016. Why should farmers in Brazil change to Integrated Agricultural Production Systems? International Journal of Agriculture and Environmental Research. 2, 18.

Chapter 7 **Carauta, M.**, Latynskiy, E., Mössinger, J., Gil, J., Libera, A., Hampf, A., Monteiro, L., Siebold, M., Berger, T., 2017. Can preferential credit programs speed up the adoption of low-carbon agricultural systems in Mato Grosso, Brazil? Results from bioeconomic microsimulation. Regional Environmental Change. 27, 675.

Chapter 8 **Carauta, M.**, Guzman-Bustamante, I., Meurer, K., Troost, C., Hampf, A., Rodrigues, R., Berger, T., Assessing policy measures to reduce greenhouse gas emissions from crop, livestock and commercial forestry plantations in Brazil's Southern Amazon. Agricultural Economics (*submitted on 13.08.2018, currently under review*).

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Acknowledgments

I would like to express my gratitude to Prof. Thomas Berger for his supervision, his support, his advices and assistance with manuscript revisions and submissions through the development is this thesis. I would like also to express my deepest gratitude to my wife for her love and companionship and for always been there when I need. In addition, I would like to thank my colleagues from the Department of Land Use Economics in the Tropics and Subtropics (490d) of the University of Hohenheim for their contributions and discussions, specially to Christian Troost and Evgeny Latynskiy. I would like to further thank Christian Troost for his support with MPMAS modeling and methodological debates. Furthermore, I would like to thank my co-authors and colleagues: Anna Hampf for parameterizing MONICA model, running several crop yield simulations and assistance with article elaboration (comments, critiques and revision), Affonso Libera for his insights on crop production in Mato Grosso and his assistance with MPMAS and MONICA model parameterization, Lucas Sousa for his support with introducing sunflower production in MPMAS and MONICA models, Katharina Meurer for modeling nitrous oxide on CANDY model, and Ivan Guzman-Bustamante for his support with modeling greenhouse gas emissions in MPMAS model.

This research was partially financed by the CarBioCial project of the German Federal Ministry of Education and Research (BMBF). I thankfully acknowledge the scholarships given by the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES) [grant number BEX-10421/14-9]. I am grateful to Embrapa Agrossilvipastoril and IMEA for the technical materials and knowledge provided. Special thanks to Eric Bönecke and Dr. Uwe Franko for their support with parametrizing CANDY model. The simulation experiments were performed using the High-Performance Computing program (bwHPC) from the state of Baden-Württemberg.

Introduction

With the current forecast of the world population reaching 9.8 billion in 2050 (United Nations, Department of Economic and Social Affairs, Population Division 2017) and anthropogenic warming and sea level rise (Intergovernmental Panel on Climate Change 2007), our society faces a significant challenge nowadays to eradicate hunger and poverty while preserving natural resources and reducing greenhouse gas (GHG) emissions. In this context, Brazil plays an important role since it is one of the most significant players in global food production and hosts a variety of ecosystems and about 12% of the Earth's biodiversity (Oliveira et al. 2017). Consequently, land use change in the Brazilian agriculture frontier has a direct impact worldwide.

The most dynamic agricultural frontier in Brazil is in the Mato Grosso (MT). The federal state of MT produces a large part of Brazil's agricultural commodities. The third largest state by area in Brazil, MT covers an area as large as Germany and France taken together. It also leads the national production of soybean, maize, cotton and holds the country’s largest cattle herd (Brazilian National Supply Company 2018). MT is also crucial for its biodiversity since it has three different ecosystems: the Amazon rainforest, Cerrado (savannah vegetation) and Pantanal (wetlands). The MT agricultural sector is mainly characterized by large-scale commercial farms where highly mechanized double-crop systems currently prevail.

One main comparative advantage in MT is the use of double-crop systems (favored by its well-defined rainy season). On the one hand, it increases farm income and reduces pressure on agricultural land use. On the other hand, the use of intensive monoculture in the grain production or the use of inappropriate practices can degrade the physical (erosion, compaction and reduced infiltration rates of water in the soil) and biological (decomposition of organic matter) properties of the soil and, increase the occurrence of weeds, pests and diseases (Kluthcouski et al. 2003; Martha Jr. et al. 2006). Monoculture also generates intense competition between plants and can also lead to high climate and market risk, as well as cash flow unbalance (Martha Jr. et al. 2006).

In this context, strategies for sustainable food production must be sought and encouraged. To this end, this doctoral thesis examines options to improve farming systems in MT and evaluates policy measures that could promote the adoption of low-carbon agricultural systems. We further subdivide this objective into the following specific objectives:

(a) Evaluate economic trade-offs in double-crop production systems;
(b) Simulate crop yield response to different climatic conditions, soil types, sowing dates, crop rotation schemes, fertilization rates and macro-regions;
(c) Estimate the magnitude of the biophysical and socio-economic dimension of yield gaps;
(d) Simulate the diffusion path of sunflower, its economic impact at farm level and identify barriers to its adoption;
(e) Evaluate policy measures to promote the adoption of low-carbon agricultural systems;
(f) Estimate the full distribution of greenhouse gas emissions related to agricultural land-use change.

To this end, an Integrated Assessment (IA) approach that simulates farm-level decision-making and agricultural land use change was developed. This approach takes into consideration heterogeneity and interdependencies among agents and their environment and 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).

The main component of our IA application is the agent-based software package MPMAS which simulates farm-level decisions and agricultural land use change. The second component is the MONICA software, which was used to estimate crop yield responses of different cultivars, nitrogen fertilization rates, soil types, and climatic conditions. This coupling allows us to assess farmer decision-making and policy response subject to specific local environmental conditions. The third component is the software CANDY, which simulates nitrous oxide emissions from soil microbiological processes (nitrification and denitrification).

The work comprises three major parts. Each part is subdivided into chapters that correspond to scientific articles developed during the Ph.D. program plus the final chapter that discusses all results together and concludes with recommendations and outlook for future research perspectives.

Part I ("Land use change and trade-offs in agricultural systems: The Mato Grosso (MT) case study") is subdivided into three chapters (chapters 1, 2 and 3) and is dedicated to an overview on land use change in Brazil and exploring the trade-offs on highly dynamic double-crop systems in MT. Chapter 1 ("Combating deforestation in the Brazilian Amazon: options for national and global governance") offers an overview on land-use change in Brazil, and the main deforestation drives in the Brazilian Amazon and discusses policy measures to cope with deforestation. Chapter 2 ("On-farm trade-offs for optimal agricultural practices in Mato Grosso, Brazil") introduces the modeling approach and analyzes the trade-offs of different agricultural practices in double cropping systems in MT. Chapter 3 ("Integrated assessment of novel two-season production systems in Mato Grosso, Brazil") presents a subsequent study on trade-offs of double-cropping systems and further investigate how the introduction of early maturing soybean varieties (MG VII) influences the organization of farms in MT and its economic performance.

Part II ("Alternative options to improve farming systems in MT, Brazil") is subdivided into two chapters (chapters 4 and 5) and is dedicated to evaluating alternative options to improve farming systems in MT. Chapter 4 ("The biophysical and socio-economic dimension of yield gaps in the southern Amazon – A bioeconomic modeling approach") presents an integrated assessment approach to decompose yield gaps in the Southern Amazon into their biophysical and socio-economic dimensions. Firstly, an overview of the yield gap concept is presented. Then, to capture the biophysical constraints in MT at farm-level, we simulate crop yields in response to different climatic conditions, soil types, sowing dates, crop rotation schemes and fertilization rates in five survey sites in MT. Afterward, to assess the main effects of socio-economic constraints on crop yields in MT, the agent-based model component is introduced. Then, yield gaps are decomposed into their biophysical and socio-economic components by coupling the two modeling approaches.

Chapter 5 ("How to increase farm income and land use intensification on highly mechanized double cropping systems? The case of sunflower in Mato Grosso, Brazil") evaluates the role of sunflower as a way of improving the agricultural production systems in MT. To investigate the role of innovative agricultural practice (sunflower) in increasing farm income and its impact on highly mechanized double-crop systems, we (1) simulate the sunflower production potential in MT, (2) simulate the diffusion path of sunflower adoption in MT, (3) identify barriers to its adoption, and (3) evaluate the economic impact of sunflower adoption at farm level.

Part III ("Policy measures to promote the adoption of low-carbon agricultural systems") is subdivided into three chapters (chapters 6, 7 and 8) and evaluates policy measures to speed up the adoption of low-carbon agricultural systems, more specifically, the adoption of integrated systems. Chapter 6 (“Why should farmers in Brazil change to integrated agricultural production systems?”) introduces the topic of Integrated Agricultural Production Systems (IAPS) by presenting the state of the art of integrated systems and investigating factors that may influence farmers to adopt IAPS. Chapter 7 (“Can preferential credit programs speed up the adoption of low-carbon agricultural systems in Mato Grosso, Brazil? Results from bioeconomic microsimulation”) evaluates the effectiveness of preferential credit programs to promote the adoption of IAPS in MT. This study applies a bioeconomic microsimulation that takes into account farmer economic incentives as well as the heterogeneity of local farm holdings concerning resource endowments, investment opportunities, as well as environmental, technical and market conditions. Through computer simulation, we simulate land-use change and adoption rates under alternative scenarios and provide evidence of specific credit conditions that might promote the diffusion of low-carbon agricultural systems in Mato Grosso.

Chapter 8 ("Assessing policy measures to reduce greenhouse gas emissions from crop, livestock and commercial forestry plantations in Brazil's Southern Amazon") presents a subsequent study that evaluates the effectiveness of the ABC credit line (Brazil's credit line for low-carbon agriculture) in reducing GHG emissions by the adoption of IAPS. A novel approach that evaluates a large variety of real-world agricultural production system at farm level is introduced. It combines (1) an agent-based model, (2) an agro-ecosystem simulation model, (3) a biogeochemical model, (4) life cycle inventory databases as well as data from field experiments and literature and simulates land use, farm-level decision-making, and GHG emissions.

Lastly, the "Discussion and conclusions" section discusses all results together by further exploring alternative options to improve current farming systems in MT (e.g., reducing yield gap or increasing farm income) and offers an overall discussion about how policy measures can promote the adoption of low-carbon agricultural systems and reduce greenhouse gas emissions. Finally, the thesis concludes with a discussion of the strengths and weaknesses of our integrated assessment approach, future research avenues and policy recommendations.

Chapter 1. Combating deforestation in the Brazilian Amazon: Options for national and global governance

Marcelo Carauta

This chapter has been published[1] in International Journal of Agricultural and Environmental Research in April 2016.

Abstract

Deforestation in the Brazilian Amazon has decreased over the last years, but there are still several illegal activities pushing it forward. The Brazilian government is taking a prominent role regarding reducing its greenhouse gas emissions (GHG) by voluntarily committing to GHG reductions. As GHG emissions from deforestation account for 60% of total Brazilian emission, the government has promoted several policies in this regard. Those policies are discussed to access its effectiveness to control the deforestation drivers over time. It is shown that some of those policies were able to reduce the deforestation; however, there are some indirect relationships that those policies could not capture. It is also highlight some options that could improve those deforestation policies.

1.1. Introduction

There is already a consensus in the scientific community that the greenhouse effect keeps the Earth warmer than it would be otherwise (Intergovernmental Panel on Climate Change 1990; United Nations Framework Convention on Climate Change 2006). The Intergovernmental Panel on Climate Change (IPCC) presented a report showing that the resulting emissions from human activities have been increasing the atmospheric concentrations of GHG. One of the main drivers for that is deforestation, which accounts for approximately

[1] Carauta, M., 2016. Combating deforestation in the Brazilian Amazon: options for national and global governance. International Journal of Agriculture and Environmental Research 2 (2), 17.

17% of anthropogenic GHG emissions according to the IPCC (Intergovernmental Panel on Climate Change 2007).

Brazil is the second most forested country in the world, with nearly 54% of its land territory covered by forest (Serviço Florestal Brasileiro 2013). The Amazon forest is the biggest forest in Brazil, covering 71% of that territory. Currently, Brazil is also a major food producer, and its relevance is expected to grow due to increasing global demand for food as the world's population continues to grow.

To meet the growing demand for food, producers need to increase the planted area, increase productivity and reduce post-harvest losses or a combination of these strategies. In the current context, there is a clear preference for production increase through continued yields gains. However, deforestation still exists. According to Figure 1.1, during the last five years (2010-2014) Brazil experienced a deforestation average of 5.7 thousand of km^2 per year in the Legal Amazon region (Instituto Nacional de Pesquisas Espaciais 2015).

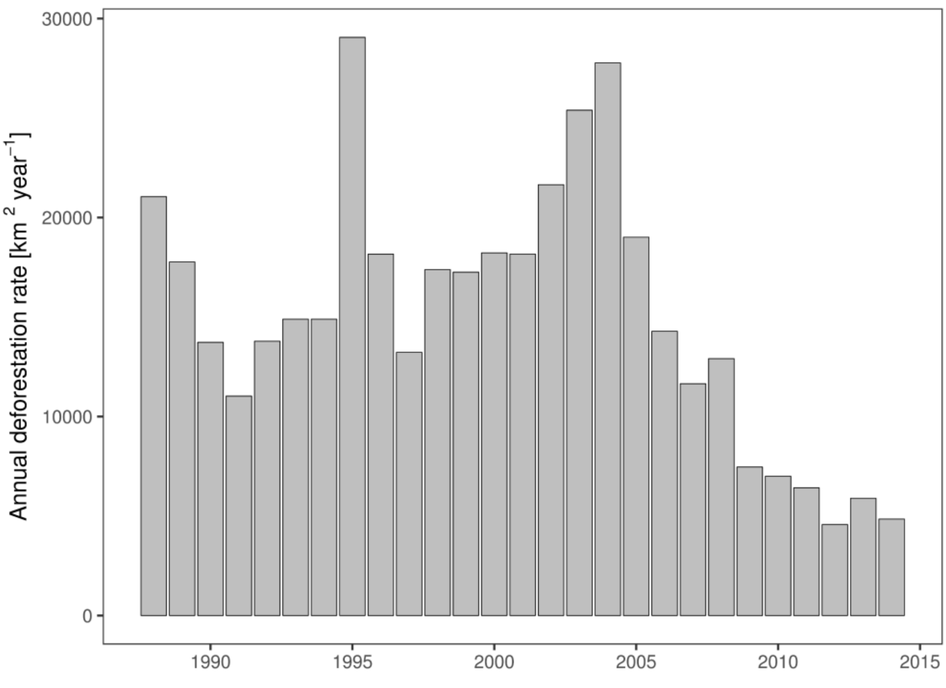

Figure 1.1 *Annual deforestation rate in the Legal Amazon region (Instituto Nacional de Pesquisas Espaciais 2015).*

The objective of this study is to analyze the main drivers of deforestation in Brazil and to evaluate the existing policy measures to reduce deforestation of native land uses. The study is organized as follows. First, the discussion about the drivers that have pushed deforestation in the past in Brazil is presented. It then leads to our review of the national and international options that are available to cope with deforestation. Finally, the policy measures that are currently being implemented are discussed.

1.2. Main Deforestation Drivers in Brazilian Amazon

To comprehend the deforestation process in the Brazilian Amazon, we need to go beyond the traditional view of direct impact (i.e.: logging, mining, infrastructure building) because some of the main drivers occur indirectly, as will be presented further. Thus, it is important to have a holistic approach to understand what was happening in the Brazilian economy during this period. The analysis starts with the decades of 1960`s and 70`s. During this period, Brazil was under an authoritarian military dictatorship, which ended on March 15, 1985.

1.2.1. History of deforestation

During the Brazilian military government, national security was one of the government's main concern, and a major demand was to fill the demographic gaps facing the country with the population concentrated in the coast, mostly in the southeast. During the sixties and seventies, the government offered many types of assistance through public policies supporting the migratory flow to the Midwest. One of those policies was the "II Plano Nacional de Desenvolvimento" (Second National Development Plan) – II PND (1975-1979), which had as its main objective the expansion of the agricultural frontier.

The migration process was accelerated by the construction of Brasília, the new capital of Brazil in 1956. This brought more investments in infrastructure and the development of new road networks linking this region with the main national centers (Farias and Zamberlan 2014).

The exhaustion of available land for agricultural use in the South and Southeast and the need to increase agricultural productivity moved production to new areas, resulting in the agricultural expansion (Oliveira and Antonia 2002).

The agricultural expansion occurred via deforestation, followed by the establishment of livestock in the Midwest. Looking to the evolution of the land use change in the Legal Amazon region (an administrative unit established by the federal government covering nine states that belongs to the Amazon Basin), Margulis (2003) showed that the area of planted pastures tripled from 1975 to 1995.

In addition to land use change, the evolution of cattle ranching in the Amazon region also triggered further deforestation. The increase in beef production in the Amazon region accounted for most of the growth in the beef industry, which also suggests an expansion of the cattle frontier to the north region (Margulis 2003). This same author showed (via a regression analysis) that the increase of one unit of animal unit per hectare meant an average increase of 1.2 percentage points in the county deforestation rate (from 1970 to 1995).

As land prices were relatively low in this period, cattle ranching was implemented in an extensive way. In 1995, the planted pastures constituted about 70% of deforested areas. However, this had a very low yield and was only viable due to its large scale and to government subsidies (Margulis 2003). The soybean production showed slow growth in the Midwest region during this period. Meanwhile, it was expanding in the south. During the sixties and seventies, soybean production expanded mostly in the south due mainly to favorable weather conditions (during that time the seed varieties were imported from the USA and were better adapted to the south conditions). Government incentives to liming, soil fertility and tax incentives for wheat (as the farmers grew both wheat and soybean in the south) and high prices on international markets also helped the expansion of soybean production in the south.

1.2.2. Indirect land use change

The expansion of a particular land-use may affect deforestation in two ways: directly by forest clearing for this purpose or indirectly by the displacement of other land-use activities from non-forest areas towards the forest frontier (Andrade de Sá et al. 2013). Therefore, this new deforestation driver is different from the former because its impact is not straightforward. It is called indirect land use change, which is defined by Richards et al. (2014) as "a land use change in one location that is responsive to a land use change in another, potentially distant location". In such situations, deforestation in one place can be motivated by a different event far away, which is difficult to measure (Arima et al. 2011).

The indirect land-use change usually materializes through a mechanism called displacement effect, which can happen in two ways: from the demand side, via an increase in the activity returns; or from the supply side through the spatial reallocation of capital from a periphery of an agricultural region to far away (usually a forested region) (Richards et al. 2014).

These authors also suggested a new mechanism that can work as a deforestation driver, the land appreciation effect. They found a positive relationship between cropland value and deforestation in Mato Grosso (MT), Brazil. Figure 1.2 depicts the land prices on agricultural land uses in MT for 2003 and 2012.

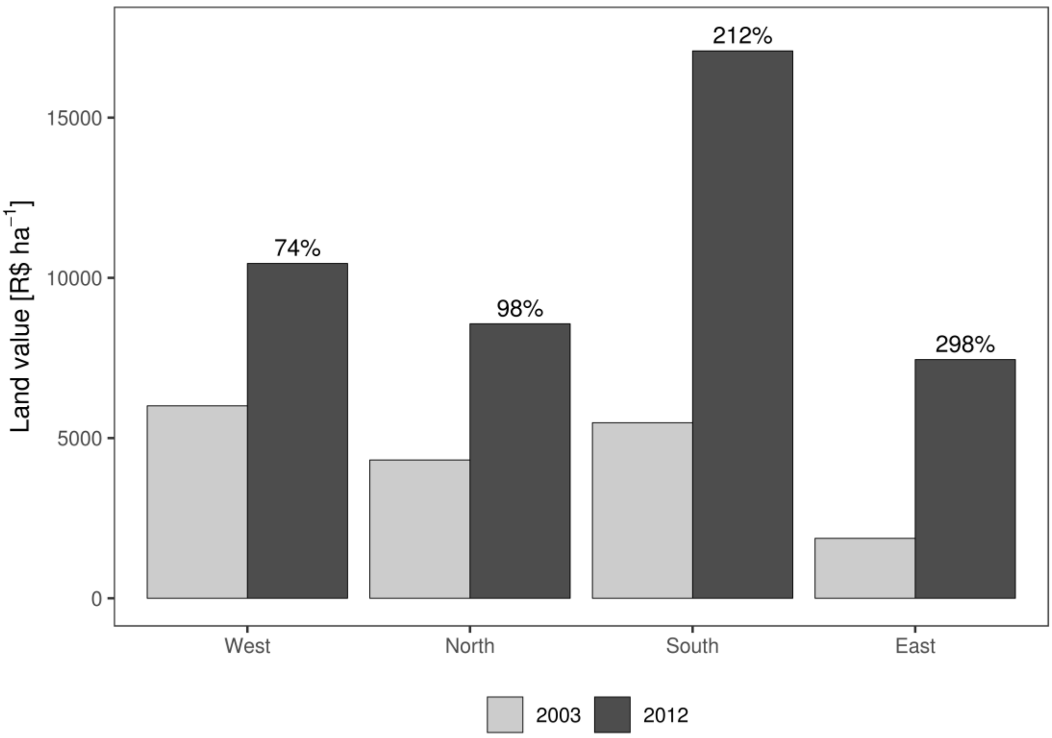

***Figure 1.2** Land appreciation on agriculture land in Mato Grosso*

The first indirect land-use change (ILUC) was caused by the sugarcane expansion in the state of São Paulo. During the late 1970`s, during the military regime, the Brazilian government was concerned with reducing its dependency on imported oil. They launched a public program called *Pró-Álcool*, which focused on substituting petrol fuels for bioethanol fuel. The program increased bioethanol demand (and, consequently, sugarcane production) by creating fuel blending mandates and by distributing subsidies to expand sugar cane production, distilleries and research on new varieties (Andrade de Sá et al. 2013).

Andrade de Sá et al. (2013) empirically assessed the ILUC effect of sugarcane in São Paulo impacting forest conversion in the Brazilian Amazon region. Their results suggest a positive relationship between sugarcane expansion and deforestation, which happened through the displacement of cattle ranching activities from São Paulo state to the Amazon region because of sugarcane expansion.

After the sugarcane expansion cycle that started in the seventies, Brazil experienced the second cycle of soybean expansion during the 1980`s and 90`s, but now in the Midwest. The main drivers for that expansion were the construction of new access routes (with the help of Brasília construction, as discussed earlier), tax incentives, favorable topography and new advances in the research (development of new soybean variables) (Brazilian Agricultural Research Corporation 2004).

This expansion in soybean production to the Midwest also caused ILUC. To statistically measure this effect, Arima et al. (2011) developed a spatial regression model capable of linking the expansion of agricultural activities to pasture conversions on distant, forest frontiers. The result showed that the ILUC effect is significant and of considerable magnitude (a 10% reduction of soybean would have decreased deforestation by 40%).

Richards et al. (2014) also analyzed the ILUC effect of soybean in the Brazilian Amazon region by using a spatial-Durbin model that enabled the explicit representation of distal impacts on land change. Their result showed that 32% of deforestation is attributable indirectly to soybean production. They also found that land appreciation in agricultural regions has replaced farm expansions as a source of ILUC.

The high return of agricultural activities increases the capital availability and, consequently, land prices. This process increased land prices in nearby areas, leading to a price increase in alternative land uses (e.g., pasture and native forest). It, therefore, raised the incentives of landowners to clear their forested properties or to sell their land and move far away, re-establishing their operations in forest areas (Richards et al. 2014).

1.2.3. '*Grilagem*' activities and the properties rights

Behind all those drivers there is one crucial factor, called *grilagem effect*, which refers to the illegal occupancy of a land property. In the Amazon Region, most lands are still owned by the federal government. These lands – that were mainly used by natives and Indigenous peoples - started to be sold to new investors in the 1970`s and 80`s. However, in most cases, it was done illegally. As an example, one could sell the same plot for more than one buyer; sell a land without its property rights by falsifying or tampering property titles and the land demarcation in a much greater extent than it was initially acquired (Loureiro and Pinto 2005).

Another problem is that sometimes the local registry office was set on fire and all the land properties documents were lost because they are not connected to other offices, and most of the documents were only stored in paper form. According to Sant'Anna and Young (2010), the inadequate definition of property rights in the Amazon region is deeply associated with the deforestation process. This uncertainty about the properties rights encourages the *grilagem* process. The first step in this process is the deforestation of native land use because they need to signalize that they have occupied that amount of land. After the logging, they implement another activity, usually cattle breeding, to try to legitimize their land ownership over the next years. After that, they could claim property rights and, with the land registry on their hands, they finally can sell the land (Instituto de Pesquisa Ambiental da Amazônia 2006).

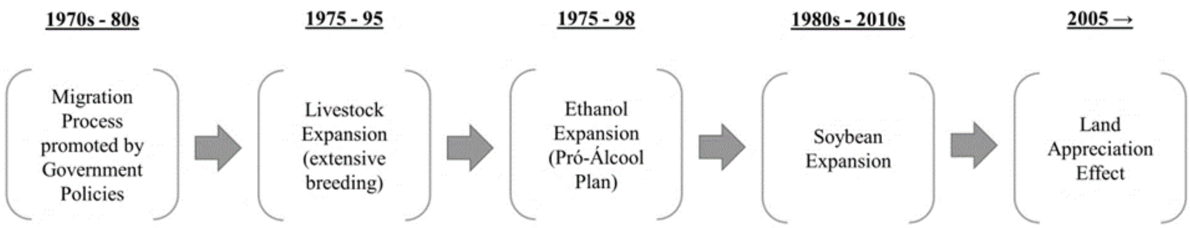

Figure 1.3 *Time line of deforestation drivers by indirect land use change in Brazilian Amazon*.

As it can be seen in Figure 1.3, the deforestation process in the Brazilian Amazon region had different drivers over the years, which are associated to particular development processes. It is essential to perceive this as a dynamic process that changes over time and is interconnected. Therefore, the policy-making process needs to follow a holistic approach/view, to capture specificities of each region and macroeconomic context.

1.3. Options for national and global governance

It is widely accepted in the scientific community and society that global warming is a significant concern. The United Framework Convention on Climate Change (UNFCCC) is an international environmental treaty which objectives to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (United Nations Framework Convention on Climate Change 2006). Several countries have ratified the Convention and meet every year in the Conference of the Parties (COP) to discuss mechanisms to reduce global warming.

As deforestation is one of the main sources of anthropogenic GHG emissions, it has been an intensely debated topic during the COP`s meetings, and several countries already started to implement some measures to reduce it. In the next two sections, it will be presented some of those actions, showing the Brazilian action in the next section and the national ones in the subsequent section.

1.3.1. Options for national governance

Throughout the 2000s, the Brazilian federal government implemented several policies to inhibit forest deforestation. The main policies are: strengthening monitoring and law enforcement; expanding protected territory; and adopting a restrictive rural credit policy (Assunção et al. 2015).

The first policy turning point was the Plano de Ação para a Prevenção e Controle do Desmatamento an Amazônia Legal – PPCDAM (Action Plan for the Prevention and Control of Deforestation in the Legal Amazon), which is the main tool from the Brazilian government to combat deforestation. The plan was launched in 2004 and introduced a new approach to deal with deforestation based on integrated action and participation of the highest levels of the federal government, which had not previously been tried (Instituto de Pesquisa Ambiental da Amazônia 2009; Assunção et al. 2015). One of its pillars is a bold satellite monitoring system that subsidizes surveillance operations in the Amazon (Ministério do Meio Ambiente 2015; Instituto Nacional de Pesquisas Espaciais 2015; Ministério do Meio Ambiente 2010). This system is carried out by the National Institute for Space Research and is due by three different instruments: PRODES (Amazon Deforestation Calculation Program), DETER (System for Deforestation Detection in Real Time) and DEGRAD (Mapping of Forest Deterioration in the Brazilian Amazon).

PRODES is one of the most advanced programs in the world for the identification and quantification of deforestation processes in forest areas. From the use of satellite images, the annual rates of deforestation are estimated from the increments of deforestation identified in each satellite image covering the Legal Amazon. Additionally, the DETER operates throughout the year and serves to warn of new deforestation focus, allowing for immediate government action against the loggers. The DEGRAD system also is done once a year, and it is designed to map areas in the process of deforestation where forest cover has not been entirely removed. This system uses the same images from PRODES but runs through a different approach/algorithm, where the main goal is to follow up the regeneration process of deforested areas already identified by the PRODES system to check if it is in a regeneration path or still suffering any degradation process.

The cooperation between different levels of government departments increased the intensity of the monitoring activities. The main collaboration was between INPE and IBAMA, which allowed the implementation of innovative procedures and techniques for monitoring, environmental control, and territorial management. In 2005 IBAMA also launched a special program focusing on improving the qualification of its personnel which also allowed a more active Amazon monitoring and law enforcement (Instituto de Pesquisa Ambiental da Amazônia 2009; Assunção et al. 2015).

In 2010 the government announced a similar plan for the Cerrado conservation, one of the most threatened Biome in Brazil, which is called Plano de Ação para Prevenção e Controle do Desmatamento e das Queimadas no Cerrado – PPCerrado (Action Plan for Prevention and Control of Deforestation and Fires in the Cerrado). The plan calls for 151 actions to reduce the vegetation loss and create alternative protection and sustainable use of natural resources of this biome.

Another landscape monitoring is done by a non-governmental entity called IMAZON - *Instituto do Homem e Meio Ambiente da Amazônia*, which is a non-profit research institution classified as a Civil Society Public Interest Organization (OSCIP), whose mission is to promote sustainable development in the Amazon (Instituto do Homem e Meio Ambiente da Amazônia 2015). This system is called *Sistema de Alerta de Desmatamento* (SAD) and, although it uses the same satellite image from DETER, it adopts a different approach which allows the identification of deforestation in areas above 10 or 12 hectares (while DETER used above 25 ha - but nowadays 6.25 ha) and avoids the cloud cover (a major issue in DETER). Despite suffering criticism from the federal government, the SAD is adopted by different levels of government as well as civil society organizations.

The second policy turning point was in 2008 with the introduction of three new policy rules. The first one was the approval of a new rule by the Brazilian National Monetary Council (CMN) including environmental conditions for landing credit to the Amazon Biome. This policy increases the difficulty in obtaining funds for producers who deforest illegally (Brazilian

Institute of Environment and Renewable Natural Resources 2015). In addition, the credit release should also observe the recommendations and restrictions of the *Zoneamento Ecológico-Econômico*, which is a government instrument for the organization of the territory.

The second policy was the passing of a Presidential Decree (6.312) in December of 2007, which established the legal basis of the identification of municipalities with high rates of deforestation and the application of differentiated actions towards them. The municipalities identified in that list were subjected to more rigorous environmental monitoring and law enforcement. Any Legal Amazon municipality could be added to that list of "priority municipalities," and the exiting was conditioned upon a significant reduction of deforestation (Assunção et al. 2015).

The approval of the Presidential Decree (6.514) was the third policy. This policy established the guidelines to the federal administrative process regarding investigating and penalize environmental violations, allowing them to be completed quickly. These measures brought greater robustness and regulatory stability to these administrative processes (Assunção et al. 2015).

Parallel to the PPCDAm's efforts, the creation of protected areas (Unidades de Concervação - UC) gained momentum in the mid-2000s (Assunção et al. 2015). According to Soares-Filho et al. (2010), in 2009 around 54% of the remaining forest of Brazilian Amazon was under the protection of UC. Those authors analyzed the effect of the Brazilian Amazon PAs on deforestation and found that they showed an inhibitory effect. Therefore, effectively implemented PAs in zones under threat offers high payoffs for reducing carbon emissions (Soares-Filho et al. 2010). Another advantage of the UCs is that they reduce the pressure for the *grilagem* activities as it reduces the uncertainty about the property rights. By changing the land status from government land to UC, the government reduces the land offer (withdraws it from the market) and minimizes the expectation of improper appropriation of property (the primary driver of the *grilagem*).

An initiative to reduce deforestation rates in the Amazon biome, which started without the government initiative, was the Soy Moratorium. It was the first voluntary zero deforestation agreement in the tropics, which began in July 2006. Pressured by the environmental groups, retailers, nongovernmental organizations and Brazil's overseas customers, Brazilian Vegetable Oil Industries Association (ABIOVE) and the National Grain Exporters Association (ANEC) – which accounts for more than 90% of the soybean commercialization in the country –

announced the signing of the Soy Moratorium. This agreement committed these major soybean companies not to purchase or trade soybean produced in areas deforested areas after 24th July 2006 in the Amazon biome (Rudorff et al. 2011; Rudorff et al. 2012; Gibbs et al. 2015). In 2008 the Brazilian government also ratified the agreement.

Since 2006 the Soy Moratorium has been renewed, and some studies have analyzed its effectiveness (Rudorff et al. 2011; Rudorff et al. 2012; Gibbs et al. 2015). According Gibbs et al. (2015), in the two years preceding the agreement, approximately 30% of the soybean expansion was made by deforestation while after the agreement its dramatically decreased to 1%. Another study showed that, in the fourth year of monitoring, the soybean area represented 0.39% of the of the total deforested area during the moratorium (Rudorff et al. 2012).

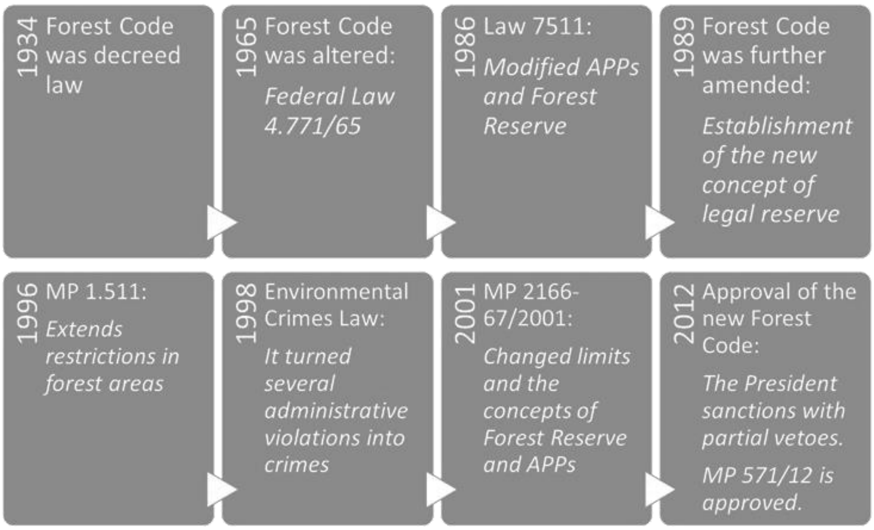

Figure 1.4 *History of Brazilian environmental legislation*[2].

During the history, the Brazilian Government has changed the environmental legislation several times. It has been in a constant process of improvement to capture the macroeconomic context of each different point in time, as it can be observed in Figure 1.4. Although the pursuit to control the deforestation and improve forest conservation lead to an intense reformulation of environmental policies, these continuous changes also create an environment of uncertainty for farmers and the private sector. Further information about the government policies presented

[2] MP = "*Medida Provisória*" - *Provisional Regulation*; APPs = "*Área de Preservação Permanente*" - *Permanent Preservation Area.*

in this section can be obtained in Table 1.1 Brazilian policies to reduce deforestation, which shows a summary of all those government policies, their aims, and instruments.

Table 1.1 *Brazilian policies to reduce deforestation*

Policy	Aim	Instruments
PPCDAm	Combat deforestation on Amazon Region	Satellite monitoring system and New Management Approach
PPCerrado	Combat deforestation on Cerrado Region	Monitoring and Control; Protected areas and regional land planning; and Promotion of sustainable activities
SAD (non-government policy)	Monitoring deforestation in the Amazon Region	Satellite monitoring system
CMN (Resolução nº 3.545)	Combat deforestation on Amazon Region	Environmental conditions for landing credit to the Amazon biome
Presidential Decree (nº 6.312)	Monitoring and law enforcement	Application of differentiated actions towards municipalities with high rates of deforestation
National System of Units of Conservation	Sustainable development and land conservation	Establishment of Conservation Units
Soy Moratorium	Combat deforestation on Amazon Region	Agreement to not purchase soy grown on lands deforested after July 2006 in the Brazilian Amazon

1.3.2. Options for global governance

As the emissions of greenhouse gas from deforestation and forest degradation accounts for nearly 20% of global GEE, this topic has been widely discussed in international debates on climate change (i.e.: COP – Conference of the Parties). It is already understood that the forest will only be kept standing when the earnings with its conservation becomes higher than the potential gain to its conversion for other purposes. In this sense, the most powerful economic mechanism for conservation of large amounts of forests may be based on the environmental services provided by standing forest (i.e.: Amazon Fund for Forest Conservation and Climate Protection) (Centro de Gestão e Estudos Estratégicos et al. 2011).

This topic was in debate in several occasions but in different approaches (e.g., COP-9 in Italy, COP-11 in Montreal and COP-12 in Nairobi. One of the main ideas was that tropical countries are responsible for stabilizing the world climate through its forests and thus the costs to keep them standing should be shared by all. The concept of Reducing emissions from deforestation and forest degradation (REDD) was introduced in 2005 and stands for a mechanism for mitigating climate change through reducing net emissions of greenhouse gases through enhanced forest management in developing countries.

This concept has been expanded to REDD+ where ‘plus’ denotes the conservation of forests, enhancement of forest carbon stocks and sustainable management of forests. This new mechanism will provide positive incentives to developing countries who take one or more of the following actions to mitigate climate change: (a) Reducing emissions from deforestation; (b) Reducing emissions from forest degradation; (c) Conservation of forest carbon stocks; (d) Sustainable management of forest; and (e) Enhancement of forest carbon stocks.

Venter and Koh (2012) review the main opportunities and challenges for REDD+ implementation. According to these authors, REDD+ is currently the most promising mechanism driving the tropical forest conservation due to its ability to harness funds and to use them in a more effective way. However, to emerge as an important policy to truly change the reality worldwide, it needs to present low transactions costs and high-volume carbon markets or funds in order to fulfill its goals (Venter and Koh 2012).

Another subject that the global governance should address is the Indirect Land Use Change (ILUC). As it was showed above, a major share of deforestation can be explained by ILUC (in Brazil firstly by sugarcane and by soybean in the recent years). As ILUC might occur in a neighboring area or even in another country hundreds of miles away, its causes and consequences can be difficult to identify, measure and address. On the other hand, it is already a concern for some countries and there are, already, some policies that try to address it.

The most well-known case is biofuel production. When biofuels are produced on existing agricultural land, the demand for food production still remains, and therefore, it may lead to someone producing more food and feed somewhere else (European Commission 2012). Thus, this might lead to conversion of forest to agriculture land, therefore, to a release of substantial amount of CO_2 emissions.

The European Commission has been working to address ILUC in Biofuel production. The main goal of those new rules is to make biofuels used in the European Union (EU) more sustainable, helping them to reduce further GHG emissions and encourage greater market penetration of advanced biofuels. Some of the actions that they have been addressing are: (a) including ILUC factors in the official reports by fuel suppliers and Member States; (b) providing incentives for biofuels with no or low indirect land use change emissions (second and third generation – advanced biofuels) and (3) limiting the amount of biofuels that can compete with food production (mainly first generation – conventional biofuels) (European Commission 2012).

1.4. Further discussions

It is essential to consider Brazilian history to fully understand the deforestation process in the Brazilian Amazon because the deforestation process is dynamic, and its drivers change over time.

One of the main deforestation drivers nowadays is the soybean expansion in the Savanna and Amazon region. Some policies already tried to deal with that like the Soy Moratorium – which started from nongovernmental organizations and civil society organizations and, later, received government support. However, as discussed above, the principal amount of deforestation through soybean production does not come directly, but indirectly (through ILUC effects). In this sense, it is vital for Brazilian policymakers to comprehend how this process works to properly incorporate it into their policies, to mitigate those drivers effectively.

Another factor that is not easy to be seen because it is hidden, with an indirect effect, is the property right issue. The Brazilian Government does not have an integrated system to manage the registry offices properly. Therefore, in those more remote areas, there is no certainty about the property rights (it is common to farms has more than one owner). Another issue is that a significant amount of land is still Government property. Those two factors together encourage the *grilagem* activities (illegal occupancy of land property), the main driver for Amazon deforestation nowadays. Thus, modifying the incentive framework concerning land tenure could help reducing deforestation. This could be accomplished by (a) land regularization policy; (b) establishment of an allocation policy for all public lands; (c) establishment of a unique system for property titles; (d) effective surveillance for property registry offices and; (e) data crossing between land agencies at the three levels of government.

The Brazilian government has been applying several different policies over the past year, and they have been mostly successful, managing to reduce the deforestation rates dramatically.

However, deforestation still, and there are still several illegal activities pushing it forward. Law enforcement has been improving over the last years due to the use of satellite images and government agencies collaboration but, yet, it is not sufficient to cover the whole Amazon territory due to its vast land size and to restricted resources from those surveillance agencies.

Some deforestation drivers are linked with the macroeconomic conditions. It was shown that the deforestation has a positive relationship with land value (through the land appreciation effect), to the exchange rate (exchange rate depreciation increases the local commodity prices) and to the commodities prices (if crop or pasture profitability rises landowners will have a greater incentive to clear their forested properties). In this sense, it is important to develop an economy based on forest resources in a way to sustainable explore the environmental services such as maintenance of biodiversity, water cycling and carbon stocks that the Amazonian forest produce.

The international community also plays an essential role in the Amazon Forest Conservation. There are several of countries that had been used their native forest to their national development. As the Amazon Forest offers several of environmental services to the world, it is very important that those who benefit from its services also engage in its preservation. Another fact is that the world population increase has been pressuring the world demand for food and Brazil has been supplying a significant share on that. Therefore, to avoid food production pushing the deforestation in the Amazon region, it is essential that those countries (high food demanding) also contribute to the preservation of the Amazon forest. One example is the Amazon Fund (Fundo da Amazônia), which is a mechanism proposed by the Brazilian government at the COP-12 aiming to reduce greenhouse gas emissions from deforestation and forest degradation (REDD) by the voluntary contribution of developing countries. In March 2009, the Amazon Fund received its first donation of $ 110 million from the Norway Government (Ministério do Meio Ambiente 2008).

To adequately address the Amazon deforestation issue, the Brazilian government should modify its approach, considering some new aspects/issues that are already discussed in the literature or other countries. Some of those are relatively easy to accomplish but others are challenging and, thus, the Brazilian government should conduct its policy wisely to achieve its goals to reduce GHG emissions and deforestation rates.

Chapter 2. On-Farm trade-offs for optimal agricultural practices in Mato Grosso, Brazil

Marcelo Carauta, Affonso Libera, Anna Hampf, Rafael Chen, José Maria Ferreira Jardim da Silveira, Thomas Berger

This chapter has been published[3] in Revista de Economia e Agronegócio (*Brazilian Journal of Economics and Agribusiness*) in November, 2017. A previous version has been published[4] in the Proceedings of 54th Congress of the Brazilian Society of Economy, Administration and Rural Sociology.

Abstract

In order to keep yield advances, farmers in Mato Grosso (MT) have been adopting several technological innovations. As a consequence, agricultural production systems in MT have become complex and dynamic since farmers have to consider the increase of decision variables when planning and implementing their farming practices. These variables are widely spread across many distinct topics, bringing them together and summarizing information from diverse fields of research has become a difficult task in farmers' decision-making process. Therefore, we performed an Integrated Assessment simulation experiment with a region-specific bio-economic component to assess trade-offs between different agricultural practices in a double cropping system. The simulation experiment was carried out with MPMAS, a multi-agent software package developed for simulating farm-based economic behavior and human-environment interactions in agriculture. Crop yields were simulated with the Model of Nitrogen and Carbon dynamics in Agro-ecosystems (MONICA). Our simulation results show a trade-off between lower soybean yields with the flexibility of double cropping when soybean with shorter maturity cycle is introduced. Results also captured regional differences in terms of land

[3] Carauta, M., Libera, A., Hampf, A., Chen, R., Silveira, J.M., Berger, T., 2017. On-Farm trade-offs for optimal agricultural practices in Mato Grosso, Brazil. Revista de Economia e Agronegócio 15 (3), 299–322. 10.25070/rea.v15i3.

[4] Carauta, M., Libera, A., Chen, R., Dantas, I., Hampf, A., Silveira, J.M., Berger, T., 2016. On-Farm trade-offs for optimal agricultural practices in Mato Grosso, Brazil, in: Anais do 54º Congresso da Sociedade Brasileira de Economia, Administração e Sociologia Rural, Maceió, Brazil.

use share of different crops and farm configurations of double cropping. These results provide key insights into a farmer's decision-making process depending on a multitude of decision variables.

2.1. Introduction

Agricultural production places Brazil amongst the most important worldwide economies. For the past three decades, Brazilian grain and livestock production have grown strongly and the total agricultural output more than doubled compared to the early 1990s. According to the Food and Agriculture Organization (FAO), Brazil is the second largest producer of soybean, the third largest producer of maize, and the fifth largest producer of cotton lint (Food and Agriculture Organization of the United Nations 2017).

Located in the Brazilian mid-western region, the state of Mato Grosso is the largest internal producer of agricultural commodities. It leads the production of soybean, maize, cotton and sunflower and holds the largest cattle herd in the country (Brazilian National Supply Company 2017). The state is also known for its biodiversity, holding three different biomes: Cerrado (Brazilian savanna), Pantanal (tropical wetland) and Amazon Rainforest. Despite being a large agricultural producer, Mato Grosso still preserves approximately 60% of its native forest (Instituto Mato-Grossense de Economia Agropecuária 2017).

The main aspect that distinguishes this region from others is the possibility of growing two crops per agricultural year: one during the rainy season and one in the second (dry) season, the so-called "safrinha". This creates new opportunities for farmers to generate revenues, to intensify the use of production factors (land, input, machinery, and labor), and to draw different strategies to overcome market fluctuations and climate instability. Second season maize production is nowadays responsible for 66% of the national maize production while it was 11% two decades ago and, therefore, plays an important role in reducing the pressure for increase in planted area (Pires et al. 2016).

Brazil's agricultural sector is experiencing an intensification process that led to a considerable increase of production without expanding the cultivated area. Within the last 10 years, grain production grew by 72% while cultivated area increased only by 22% (Brazilian National Supply Company 2017). The state of Mato Grosso has intensified production and expanded the agricultural frontier into the savannas. Although expanding the agricultural frontier partly explains the increase in production, technological innovation in agriculture is the main factor boosting production.

The development of new seeds is the most important innovation enabling crops to adapt in different climatic and soil conditions (Vieira Filho and Silveira 2011). Technological advances in genetically modified organisms (GMOs) and short maturity cycle seeds with higher productivity, which are designed to overcome natural instabilities and pests were also key factors for this process. Innovations in soybean, maize and cotton seeds broadened possibilities in the decision-making process of production practices, input requirements, and crop management. In Mato Grosso, farmers access a wide range of seed varieties with specific genetic characteristics that may optimize production and even reduce operational costs.

Usually, agricultural innovations occur within research institutions as well as high-tech agricultural properties (Vieira Filho and Silveira 2011). However, it is observed that diffusion and adoption of technologies in agriculture take place in a modular (Frenken 2006) and heterogeneous (Rogers 2003) way, which influences adoption criteria by farmers. This process is a complex issue because it leads farmers to face more combinations of production practices, drastically increasing the number of decision variables farmers need to consider during their decision-making process.

The agricultural system in Mato Grosso consists of producing soybean, maize, and cotton, which are grown in different crop rotation set-ups during the rainy season and second season. Each crop has different maturity cycle and seed technology (conventional seeds, herbicide tolerance and/or insect resistance), which can be combined with a large range of sowing dates and fertilization applications. In turn, farmers have a wide range of possibilities when deciding which crop rotation combination would achieve the highest yield and income given market and environmental conditions.

Hence, the general objective of this study is to analyze the trade-offs of different agricultural practices in double cropping systems in Mato Grosso, Brazil. The specific objectives are to: (1) assess the impact of different crop cycles and sowing dates on crop yield; (2) estimate the economic outcome of different crop management practices; and (3) simulate land use of optimal agricultural practices.

In this way, this article aims to address the decision variables farmers need to take into consideration and the decision variables' impact on production system's gross margins and farmers' decision-making. As a research hypothesis, we argue that the technology diffusion process increased farmers' decision variables and the complexity of those systems. In addition, we argue that the decision variables need to be taken into consideration in a holistic approach, to achieve an optimal outcome.

We conducted a quantitative analysis with a farm level approach on farm systems in Mato Grosso and performed a region-specific bio-economic micro-simulation experiment by which we captured the interregional differences between farms, farm-based economic behavior and farmer-environment interactions in agriculture. The simulation results provide detailed information on how the decision variables affect the production systems. Biotechnological innovation broadened the number of crop rotation and crop management practices which, in turn, enabled farmers to better manage and forecast production. The results of this article provide a full understanding of economic and environmental aspects of different combinations of agricultural systems in Mato Grosso.

2.2. Literature Review

Since agricultural activities involve a wide range of decision variables in terms of which cropping systems and/or seed varieties to choose, farmers face a series of risk and uncertainties when it comes to the decision-making process. Farmers are confronted with economic uncertainties as well as environmental risks such as severe weather, pests, and seasonality. In order to avoid or reduce impacts from uncertainties and risks, farmers rely on the diffusion of new products and processes, which play an important role in transforming contemporary economies (Silverberg et al. 1988). This diffusion process changes over time due to the heterogeneity of adopters, who follow different criteria when adopting a certain technology (Rogers 2003; Dosi 1982).

Advances in biotechnology are a key factor in the development of the agricultural sector. According to Valois (2001), genetically modified plants can provide an increase in production and yields, reduce production costs and improve pest management. The main transgenic traits are insect-resistant (IR), herbicides-tolerant (HT), and more recently, a combination of the two (HTIR). The impacts of transgenic varieties are diverse and vary across countries especially due to differences in environmental pressures and pest control management. While GMOs in some countries reduced production costs, in others they decreased production due to weak agricultural practices (Finger et al. 2011).

In Argentina, Qaim and Zilberman (2003) found no economic advantage of HT soybean over conventional (CONV) soybean in terms of gross margin, yield and production costs.

However, when regarding herbicides application, there was a cost reduction with HT soybean. Other benefits such as lower demand for pesticide and better pest control management were observed in countries such as China, India (Bennet et al. 2005; Pray et al. 2002; Qaim and Zilberman 2003), South Africa (Thirtle et al. 2003; Gouse et al. 2005) and Pakistan (Ali and Abdulai 2010). In terms of gross margin, Qaim and Traxler (2005) found that, on average, HT soybean achieved an advantage of US $ 23 per hectare.

In Brazil, HT cotton, compared to conventional varieties, requires less field operations and weed control (Alves et al. 2012). Additionally, it requires less herbicide and fewer mechanic and manual operations, thus reducing costs and environmental impacts. On the other hand, Seixas and Silveira (2014) found HT soybean production increased environmental impacts. Duarte et al. (2006) found evidence that insect-resistant (IR) maize varieties presented agricultural and economic advantages such as lower demand for labor and pesticides. Additionally, compared to conventional varieties, IR maize varieties achieved higher yields.

In addition to technological advances, different types of farming practices impact crop yields and risk levels farmers face. Sowing date is an important decision variable as it allows farmers to draw different production strategies by combining crop rotation and different seed varieties. By adopting seed varieties with shorter maturity period, farmers can increase their cropping frequency (harvest more than one crop per growing season), which has an impact on crop yields. Yields from soybean with shorter maturity cycle may be lower compared to soybean seeds with longer maturity cycle; however, growing an additional crop may offset yield losses adopting soybean seeds with shorter maturity cycle. The possibility of increasing cropping frequency by sowing earlier or adopting seed varieties with shorter maturity cycle, however, is affected by climate variability. According to Pires et al. (2016), increased climate variability may affect farmers who sow soybeans early to grow either maize or cotton in the second cropping period in northern Brazil. Cohn et al. (2016b) indicate that an increase in local mean temperature in Mato Grosso will decrease cropping frequency and vice versa. In case of a higher mean temperature, farmers may offset potential yield losses by sowing soybeans on a later date. However, Pires et al. (2016) suggest that this will then affect the possibility of double cropping and yield levels of maize and cotton.

The sowing date directly affects crop yields due to different rainfall regimes, temperature and incoming solar radiation (Cruz et al. 2010). Cruz et al. (2010) observed that maize and cotton varieties sown by the end of the rainy season in the Brazilian savanna presented lower yields than those sown at the beginning of the rainy season.

Sowing date is the main limiting factor for second season cotton yields. Ferreira et al. (2015) evaluated differences in productivity of cotton according to different sowing dates and found an average decrease of 28% in productivity of cotton yields when sown by the end of the rainy season due to low water supply.

As second season cotton is sown immediately after harvesting soybean, sowing dates of both soybean and cotton affect water supply for the second season. This highlights the importance of drawing production strategies to sow cotton as early as possible (Ferreira et al. 2015).

As shown by Pedrotti (2014), second season maize follows the same pattern. Usually, maize is sown in January, February or March. Crop growth is, therefore, jeopardized by a range of environmental characteristics, such as less water supply, temperature, and solar radiation. Fitting the sowing date, as much as possible, within the rainy season enables crops to grow within a suitable environment, using all production factors available, increasing the probability to achieve greater yield.

Climate variability also affects cropland area and decisions farmers make to either expand or abandon their agricultural land. Results from Cohn et al. (2016b) show that an increase in local mean temperature can lead to a decline in cropping area, which can negatively affect crop yields. With unfavorable weather conditions and low quality agricultural land, farmers may go through a process of expand-and-abandon until they find a favorable land (Spera et al. 2014). Agricultural expansion in Mato Grosso has been declining in recent years, which Spera et al. (2014) reason that scarcity of high quality land may be a contributing factor.

Another key decision variable regarding crop production is nitrogen (N) application because it directly affects crop growth and grain production and, therefore, is an important decision variable when planting cotton and maize (Teixeira et al. 2008; Orioli Júnior et al. 2011). Thus, applying a suitable source and amount of nitrogen is crucial to achieve high yields and maximize farm income (Orioli Júnior et al. 2011).

2.3. Methods and Data

2.3.1. Methodology

We implemented an integrated assessment (IA) based on a multi-agent micro-simulation model. IA is an interdisciplinary process that combines research subjects and disciplines to provide a better understanding of a complex phenomenon (van Ittersum et al. 2008). The methodology applied in this work follows the approach of Carauta et al. (2017a).

Micro and macro-economic analyses are suitable tools to analyze agricultural production systems; however, IA presents additional benefits over those. Firstly, it takes into account cross-scale issues, enabling the up-scaling of farm level data into different macro levels (i.e.: market, municipalities, states or regions). It also enables the assessment of policies by reducing the micro-macro gap (van Ittersum et al. 2008). IA allows analysis of different groups of agents and/or farms due to technical advantages in computational processes. Additionally, it enables the assessment of policy changes and technological innovations. Lastly, the model dynamics are suitable to assess long-term impacts of climate, soil conditions and farm production factors. The model simulation was done with MPMAS (Mathematical Programming-based Multi-Agent Systems), a multi-agent software package for simulating land use change in agriculture that was linked to the crop model MONICA.

To simulate farm decision-making process in agricultural systems, MPMAS uses the constrained optimization approach (Schreinemachers and Berger 2011). MPMAS has been applied in a range of studies of farm-level agricultural production system and on innovation diffusion in agriculture (Quang et al. 2014; Schreinemachers et al. 2010; Troost et al. 2015).

Our IA approach combines the economic component of a farm-level decision-making problem with a crop growth model, that was used to simulate crop yield response to different environmental and crop management conditions. The MONICA model is a dynamic, process-based crop model that describes transport and biochemical turnover of carbon, nitrogen, and water in agroecosystems (Nendel et al. 2011; The Model for Nitrogen and Carbon in Agro-ecosystems 2017). Both models, MPMAS and MONICA, were linked to an online database stored in a MySQL server. The crop yields were simulated for all climatic conditions and specific characteristics of regions, which are stored in the database. The database application MPMASQL accesses all relevant information in the database and converts it into MPMAS input. Lastly, MPMAS was integrated into a computer cluster with the use of COIN's CBC mixed-integer programming solver, specifically calibrated for this study.

Each farm agent faces three decision problems in each simulation period (one agricultural year): an investment decision, a production decision, and a consumption decision. Those problems are converted into a MILP (Mixed Integer Linear Programming model). The full MP-optimization problem for each agent consists of 2705 decision variables (63 integers) and 1925 constraints, which results in a very large number of choices in regard to the crop production system, crop management, crop rotation, and production factors (e.g. acquisition of inputs, labor, and machinery). Agents in MPMAS maximize expected farm income by choosing the optimal combination of land use, which needs to be done subject to a set of constraints, such as resource availabilities and climatic conditions, which are specified in the form of equations or inequalities. Expected farm income is calculated as the sum of expected revenue from crop production activities minus variable and fix costs.

We applied a parallel bio-economic simulation experiment in order to assess expected gross margin for specific crop production practices. For that, we developed a new MPMAS application which consisted of creating 227 artificial assets to represent all combinations of crops, maturity group, seed technology, fertilization amounts and sowing dates to simulate the impact of each specific crop practice on one individual farm holding. At the end, each simulation step (representing one real world harvest year) consisted on 995 artificial farm holdings, a combination of crop practices and regions. The full MP-optimization problem for each agent consists of 2921 decision variables (288 integers) and 2142 constraints.

A crop calendar was created to capture the timing of agricultural activities and to correctly simulate agents' resource allocation of machinery and labor over time. This calendar has a weekly resolution in MPMAS and defines the weeks in which farm activities are taking place. The crop calendar was created for each cropping system included in the model according to technical recommendation. Therefore, it is specific for each crop management practice (a combination of crop, maturity group, and seed technology). The link between crop calendar and data on labor and machinery provides estimations of weekly requirements for machinery, input, and labor. The crop calendar is also linked to the crop growth model, in which each agricultural activity is connected to daily climate data.

2.3.2. Model Parameterization

The MPMAS model was parameterized for five municipalities in Mato Grosso: Sapezal, Sorriso, Campo Verde, Tangará da Serra and Canarana. Mato Grosso Institute of Agricultural

Economics (IMEA) considers these municipalities as representative for the following regions respectively: West, Mid-North, Southeast, South Central and Northeast (Instituto Mato-Grossense de Economia Agropecuária 2010a). The agent population includes all crop-producing farm holdings in those five municipalities which are larger than 50 hectares, according to the latest agricultural census available (Brazilian Institute of Geography and Statistics 2006). At that time, there were 720 farm holdings which corresponded to 74% in terms of number and 99% in terms of cultivated area of all crop-producing farms in those municipalities. Based on these data, we produced a statistically consistent population of model agents following the Monte Carlo approach of Berger and Schreinemachers (2006). Simulated land uses are upscaled from municipality to regional level using weighting factors from the Brazilian Agricultural Census (Brazilian Institute of Geography and Statistics 2006).

Soil classes were assigned to each model agent based on the official maps of socio-ecological zoning produced by the Mato Grosso State Secretary of Planning (Secretaria de Estado de Planejamento e Coordenação Geral de Mato Grosso 2011). We assigned six different soil classes, resulting in ten possible climate-soil combinations considering the above-mentioned municipalities. Soil classes in each municipality were also linked to MONICA in order to simulate crop yield response to different soil conditions. Weather dataset from 1999 to 2013 for each of the five municipalities were taken from the Brazilian Meteorological Institute (Instituto Nacional de Meteorologia 2017) and contain the following weather data in daily resolution: maximum and minimum air temperature, sunshine hours, precipitation, wind speed and relative air humidity.

The agricultural production practices included in MPMAS correspond to the most common agricultural commodities found in each selected region of Mato Grosso: soybean, maize, and cotton (Figure 2.1). Our simulation models MPMAS and MONICA include region-specific production practices (e.g. agents in different regions employ different types of pesticides and they choose different intensity of machinery use). For soybean, we considered three different maturity groups (MG7, MG8, and MG9 corresponding to a growing cycle of less than 115 days, 115 to 126 days and more than 126, respectively), four planting dates (01-Oct, 15-Oct, 01-Nov and 15-Nov) and three technologies (Conventional - CONV -, Herbicide Tolerant - HT - and Herbicide Tolerant and Insect Resistant - HTIR). While soybean can satisfy large part of its nitrogen requirement through biological N fixation, we considered nitrogen application rates as a decision variable for maize and cotton. For maize, four different sowing dates (20-Jan, 06-Feb, 20-Feb and 06-Mar), five nitrogen applications rates (0, 40, 80, 120 and 160 kg ha^{-1}) and three technologies (CONV, IR and HTIR) were considered. For cotton, five planting dates were considered, two in the first season (15-Dec and 30-Dec) and three in the second season (15-Jan, 30-Jan and 15-Feb); as well as seven nitrogen levels (0, 90, 140, 185, 230, 280 and 450 kg ha^{-1}) and four technologies (CONV, HT, IR, and HTIR). In total, we included 227 agricultural production possibilities that were combined with specific soil fertility constraints for each region, resulting into 1990 possible set-ups that each farm agent manages every year. The complexity in an agent's decision-making increases even further as favorable climatic conditions allow a double cropping system, resulting in 40 feasible double crop combinations.

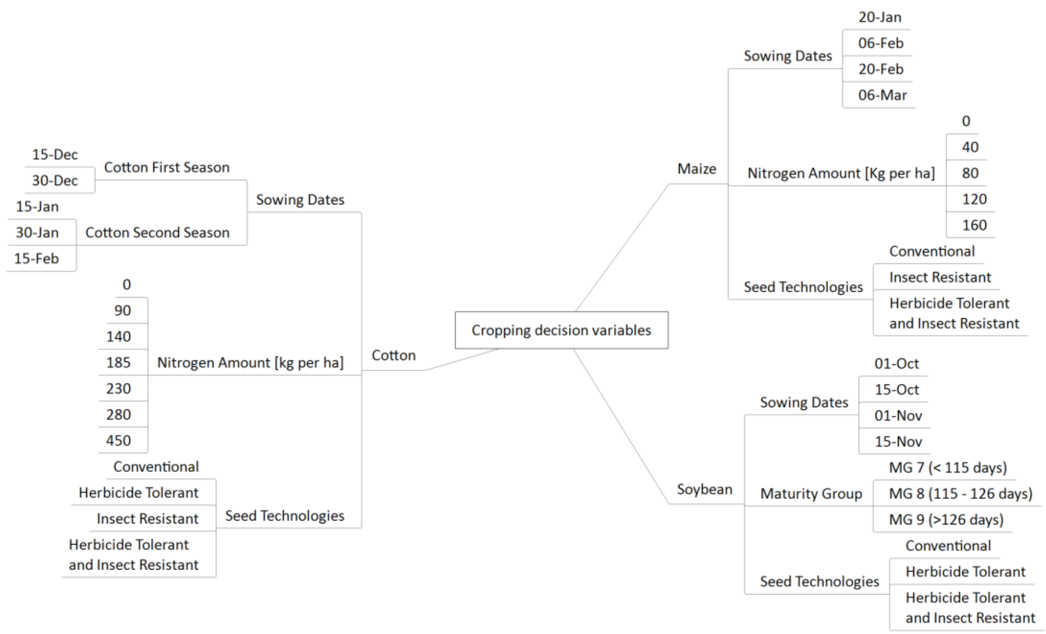

Figure 2.1 *Decision variables of simulated agricultural practices*

Different crop management practices for each agricultural production possibility were also taken into account. Crops with longer maturity cycles require more fungicide and insecticide applications; Insect Resistant (IR) crops require fewer insecticides applications; Herbicide Tolerant (HT) crops require herbicides with different active ingredients; in case of soybean HTIR, the longer the maturity cycle is, the greater is the substitution effect between the insecticide application and the genetically modified (GM) Bt toxin. Different crop technologies require different input quantities (Figure 2.2), however, also the active ingredients change according to each technology. The crop management options for MPMAS were estimated with a farm level survey from Céleres – a local agribusiness consulting enterprise – (Consultoria

Focada na Análise do Agronegócio 2018), including 157, 299, and 303 observations for soybean, maize and cotton, respectively, as well as technical advice from local experts.

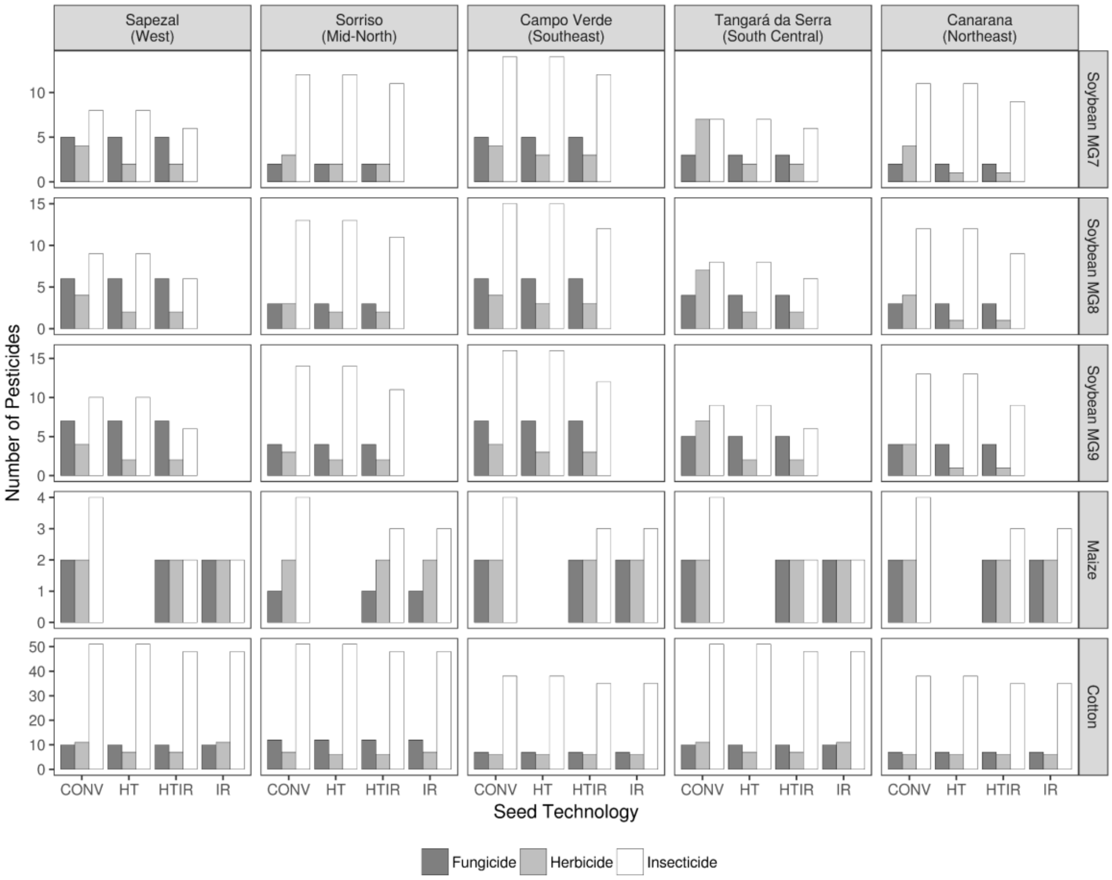

Figure 2.2 *Number of pesticide applications according to different crop management practices in five survey sites in Mato Grosso, Brazil. Seed technology: conventional (CONV), herbicide tolerant (HT), insect resistance (IR) and herbicide tolerant and insect resistance (HTIR). Soybean Maturity Group (MG).*

The estimation of production costs for each crop and region is annually done by Instituto Mato-Grossense de Economia Agropecuária (2016c). Together with farmers and experts from all stages of the production chain (i.e.: input sellers, machinery sellers, rural union), the production costs are estimated using a collaborative approach in which the concept of "modal farm" is used - a productive unit with characteristics that approximate the local reality profile to the region (CONAB). From the modal production cost, we estimated production costs for each crop, seed cycle, seed technology (CONV, HT, IR, and HTIR), and region based on technical advice from local experts. Besides the production costs, we also estimated the post-harvest costs, such as transportation, storage, processing, and taxes. The time series data for the agricultural products were also taken from IMEA, including the online price dataset (Instituto Mato-Grossense de Economia Agropecuária 2016c).

2.3.3. Model Validation

In order to assess to which extent our combined MPMAS_MONICA simulations are a good representation of the real-world observations, we applied an empirical validation in which the output from the simulation models was compared to the corresponding observed data (Fagiolo et al. 2007). For our IA approach, we used a three-step process, one for the biophysical model component and two for the bio-economic model component. The first step considered the validation of the output from the crop growth model MONICA. The validation process considered Mato Grosso`s soil and climatic conditions and used municipality-level crop yield estimations from the IBGE as observed data (Brazilian Institute of Geography and Statistics 2018). The observed yield data were compared to the simulated yield data from MONICA (and later integrated into MPMAS) (Figure 2.3). Due to lack of farm-level information on individual crop yields and management, it was not possible to validate the simulated yield at farm agent level. Instead, we compared simulated yields against observed yields at municipality level.

We used three different statistical indices to assess the crop model´s performance: Mean absolute error (MAE), root mean square error (RMSE) and Willmott´s index of agreement (d), a standardized measure of the degree of model prediction error. The validation of the crop growth model suggests that its predictions match both with the municipality level average yields and with the yield responses due to different climate conditions over the years (MAE of 385.1; 603.16; 363.6 (kg ha^{-1}); RMSE of 481.84; 836.78; 513.29 (kg ha^{-1}); d of 0.4; 0.66; 0.62, respectively for soybean, maize, and cotton - Figure 2.3).

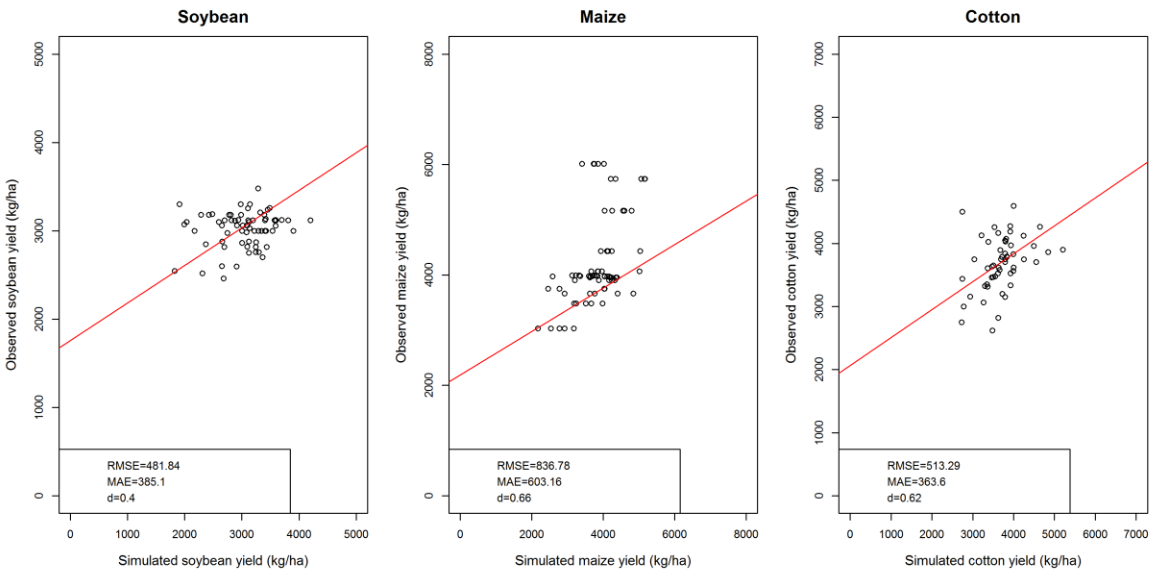

Figure 2.3 *Validation of crop yields simulated with the MONICA model for five survey sites in Mato Grosso, Brazil. The red line indicates a regression line between the simulated and observed crop yields.*

The second and third steps are related to the validation of our bio-economic model component, which was done with the MPMAS software. First, we ran a farm-level validation and after that, a municipality-level validation (Figure 2.4). Those two processes were carried out separately and were necessary because the model simulates both the behavior of individual farms and of the study area. For the farm level validation, data from the Instituto Mato-Grossense de Economia Agropecuária (2016c) was collected and, for the municipality level, municipality land use data from Brazilian Institute of Geography and Statistics (2018). The MPMAS validation of the bio-economic component took into account the different farm profiles for each region, such as land ownership, asset endowments, as well as inter-regional characteristics and constraints.

The model efficiency was estimated following Nash-Sutcliffe (an efficiency of one indicates a perfect match between the simulated and the observed data, while an efficiency smaller than zero indicates that the sample mean is a better predictor than the model). Under the farm-level step, our application has a model efficiency of 0.66, which improved to 0.81 at the municipality level step. In addition, the fitted no-constant regression lines and their calculated R-squared (0.92 for the farm level and 0.97 for the municipality level) indicate a good fit of the model results (Figure 2.4). Therefore, the validation outcomes suggest that our MPMAS application can simulate land use decisions consistently and accurately both at the farm and municipality level.

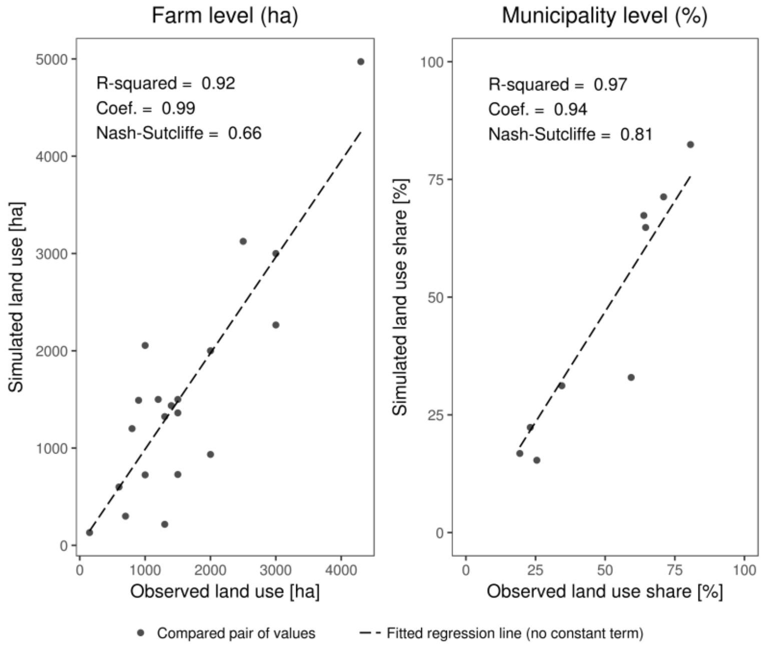

Figure 2.4 *Model Validation based on MPMAS simulation*

2.4. Results and Discussion

2.4.1. Impact of crop cycle and sowing dates on crop yields

As soybean is usually cultivated in the first season, the sowing date is not such a significant decision variable as it is for crops sown in the second season, such as maize and cotton. However, soybean yields are significantly influenced by the length of its growing cycle and according to maturity groups. As shown in the previous section, a longer maturity cycle requires additional application of pesticides, as crop exposure to pests is increased. On the other hand, a longer growing cycle has the potential to achieve higher yields (approximately 6 bags when compared to the shortest maturity group, Figure 2.5). Despite its lower yields, soybean varieties with a shorter maturity cycle allow for maize and cotton in the second season to be sown earlier, which might increase the rotation system gross margin. This result converge with Cohn et al. (2016b) findings, showing that shorter-cycle soybeans facilitate second-crop production, but reduce first-crop yields. Therefore, an agent's decision regarding crop rotation should take into consideration the trade-off between crops yields and its relative price levels.

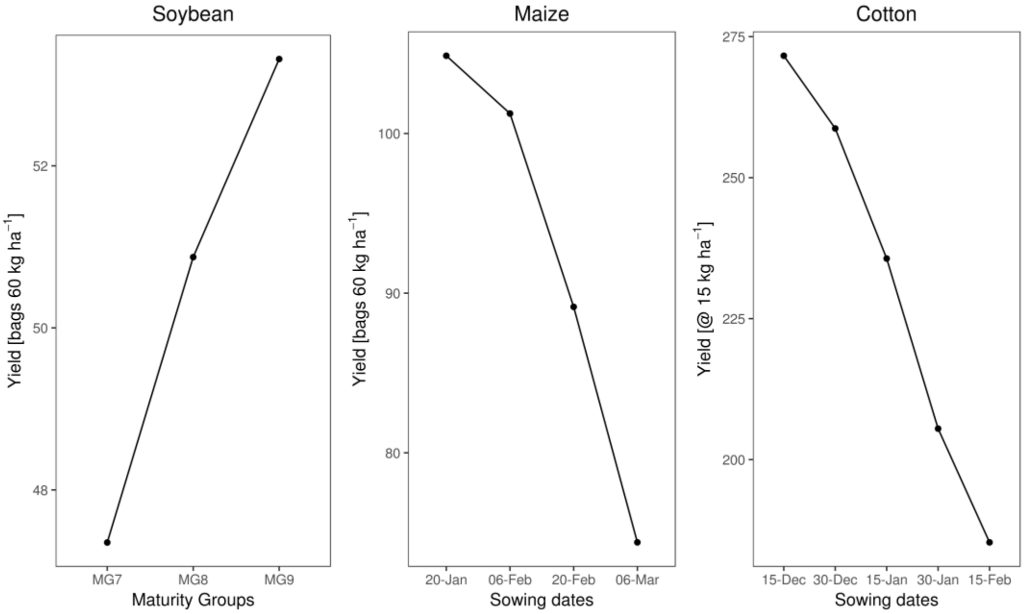

Figure 2.5 *Simulated crop yields for different maturity group and sowing dates in Mato Grosso, Brazil (average of all survey sites). Soil: Ferrasol Dystrophic; Nitrogen Amount (kg ha-1): 0, 120 and 185, respectively.*

For crops sown during the second season (maize and cotton), sowing date is a significant decision variable. On average, the latest sowing dates results in a yield reduction of 30 bags for maize and 86 arrobas (one arroba is approximately 15kg) for cotton when compared to the earliest sowing date (Figure 2.5). This can be explained by a lower supply of rainfall during the crop development phase and an increasing transpiration deficit that limits crop growth. The coefficient of variation for that decision variable was 15% for both crops. Thus, our simulation results suggest that both maturity group and sowing date are important to a farm agent's decision-making process.

As pointed out by Arvor et al. (2014), double cropping system adoption is related to high annual rainfall, a long rainy season and a low variability of the onset of the rainy season. Our simulation results additionally show that those variables are also related to the adoption of medium to late soybean varieties (such as MG8 and MG9). On the other cases, a higher share of shorter maturity cycle is observed since it favors early sowing dates at the second season.

2.4.2. Economic outcome of different crop management practices

In order to assess the impact of all decision variables in each production system, we estimated the gross margin (in Brazilian Reais per hectare) of all crop management practices.

Figure 2.6 shows that all crop practices related to soybean production presented positive gross margin. On average, soybean varieties of MG 8 and MG 9 achieve a higher gross margin when compared to varieties of MG 7, which can be explained by the higher yields these varieties achieve (Figure 2.5). The best soybean economic performance was observed in treatments with HTIR seeds, as those seeds presented, on average, an increase of 11,4% in yields in our econometric analysis from Céleres database. Soybean HT varieties achieve a higher economic performance when compared to conventional ones, due to cost reduction in herbicide application.

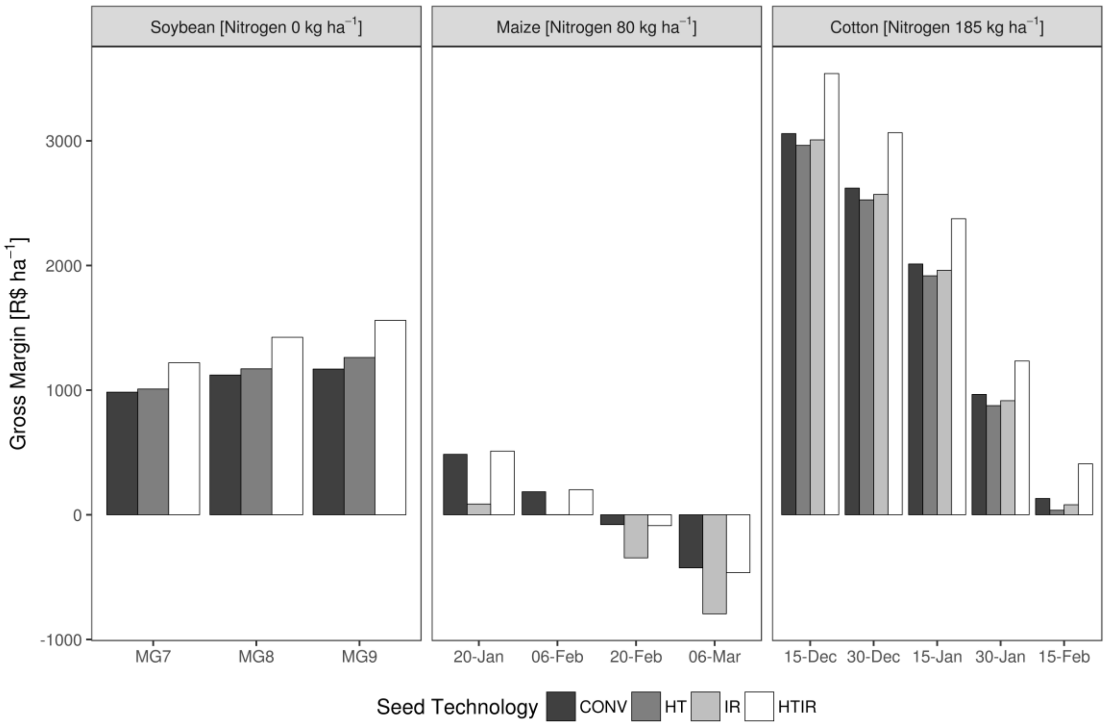

Figure 2.6 *Gross Margin per hectare for Mato Grosso (average of all regions). Seed technology: conventional (CONV), herbicide tolerant (HT), insect resistance (IR) and herbicide tolerant and insect resistance (HTIR). Soybean Maturity Group (MG).*

Due to macroeconomic conditions related to the crop season 2015/2016, maize production show, on average, negative gross margin. There are several factors which can explain this result. The first one is that yields tend to decrease with late sowing dates (Figure 2.5), which makes it very risky to grow maize with a high level of investment in technology on a later sowing date. The second reason is the current economic crisis in Brazil, which increased the inflation rate over the recent years and, consequently, production costs. Production costs were also affected by depreciation in exchange rates, as a large share of inputs (mainly pesticides and fertilizers) is imported from abroad. As pointed out by Bennet et al. (2005), high seed prices for transgenic maize varieties increased the production cost, which led farmers to avoid adopting these technologies.

It is important to note that maize is also grown for technical reasons since it increase organic matter, keeps the soil covered during the dry season, reduces soil compaction and improves water infiltration in the soil (Alvarenga et al. 2001). Another reason is that maize is easily tradable in Mato Grosso, while for others crops, such as millet, sorghum, and crotalaria this is not true. Therefore, it still makes sense to produce maize under low price conditions, but farmers will probably reduce the technology level with a combination of lower nitrogen amount and cheaper seeds.

In this study, cotton showed the highest gross margin among all crops. Crop production is more profitable when cultivated in the first season (15-Dec and 30-Dec) compared to late sowing dates. However, the crop rotation in the first case consists of growing millet, which is not sold on the market, as a cover crop from October to December. On the other hand, second season cotton is cultivated after soybean, providing an alternative source of income to the production system. It is important to note that cotton production is very complex and requires experience, expertise and a high level of investment. Therefore, despite its higher gross margin, there is still a higher share of maize adoption since cotton production requires: (1) specific soil and climatic conditions, (2) high capital/liquidity requirements (due to high production cost), (3) high machinery requirements (due to its high frequency of field operations) and (4) high investment costs (due to the use of specialized machinery, such as cotton harvester).

In regard to seed technology, our simulation suggests that the economic benefit of lower production cost from fewer herbicide and insecticide applications for HTIR seeds more than compensate the investment on those seeds, pushing the adoption of those varieties.

2.4.3. Simulated land use of optimal agricultural practices

Our simulation experiment shows that the optimal agricultural practice changes significantly according to each region. The key factor is the yield variation through all regions, which can be explained by changes in climatic and soil conditions. Mato Grosso state has nine hundred thousand square kilometers, the third largest state in area, and holds a large variety of biomes and biodiversity, which directly influences rainfall pattern, soil conditions, temperature, and solar radiation (Arvor et al. 2014; Pires et al. 2016). Therefore, despite all the agricultural practices available for each farm holding, the optimal set chosen in our simulation experiment is mostly influenced by climatic conditions. This highlights the fact that it is important to conduct an IA that integrates all key decision variables to properly assess the complexity of production systems. As an example, double cropping in Mato Grosso is more prevalent in areas with a longer period of rainy season and a higher annual mean rainfall (Arvor et al. 2014). Results from Figure 2.7 converge with the aforementioned literature, showing that areas with a longer rainy season such as Mid-North and West show higher land use share with maize and cotton.

Simulated land use share for Southeast show high level of double cropping even though rainfall levels are lower compared to other regions. This divergence show that rainfall may not be the only deciding factor of whether farmers adopt double cropping or not. Even though the average precipitation in the southeast region is smaller, there are still favorable climatic conditions to produce cotton in this region, since there cotton lint is less exposed to rain, which improves its quality. Although Northeast region had the second highest mean rainfall, Arvor et al. (2014) indicate that this region had the lowest double cropping systems and Figure 2.7 confirms this with northeast region displaying the highest level of land use share for soybean production (or the lowest level of land use share for maize and cotton combined). This figure shows that cotton production systems were more concentrated in the Southeast and West regions, while soybean and maize were more evenly applied across the state.

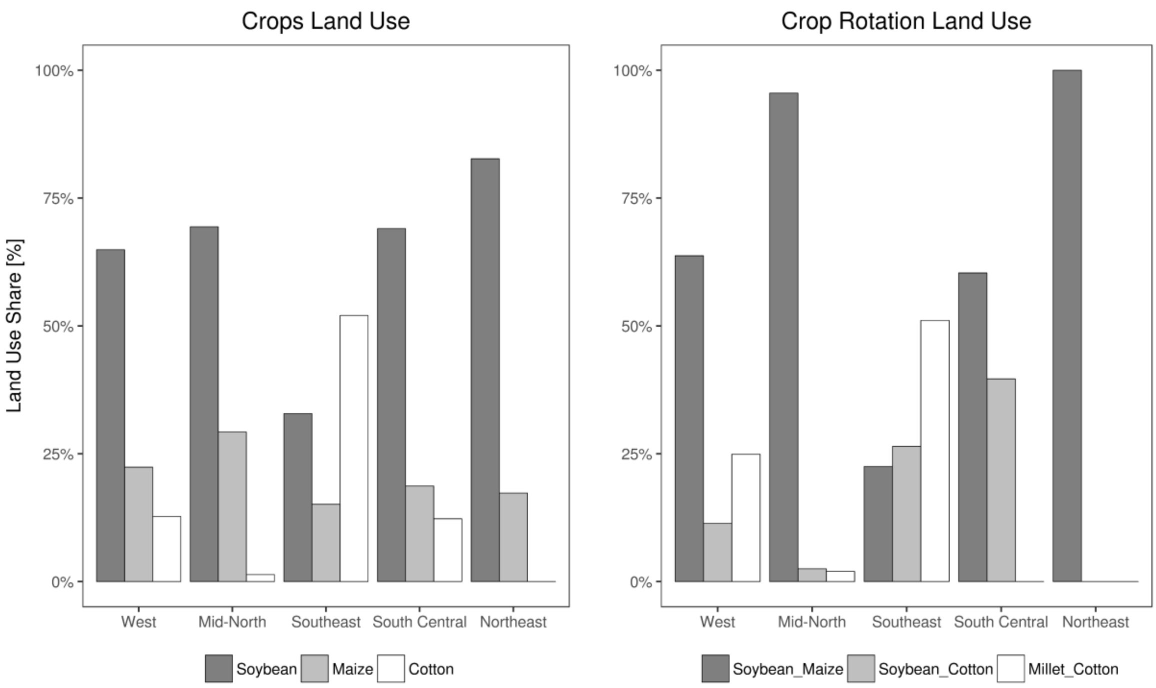

Figure 2.7 *Simulated land use of optimal agricultural practices in Mato Grosso, Brazil (upscaled to regional level using IBGE sampling weights for land use).*

Figure 2.8 shows an example of a simulated optimal land use by our MPMAS application for one typical farm in the South-Central region that implements both soybean-cotton and soybean-maize rotation systems. The farm cropland area comprises 2500 hectares, which are completely used for soybean cultivation in the first season. Due to machinery and labor constraints, it is not possible to cultivate the whole area on the same sowing date; therefore, our simulation shows that this agent should sow part on the first sowing date (01-Oct) and the remaining on the following dates (15-Oct and 01-Nov).

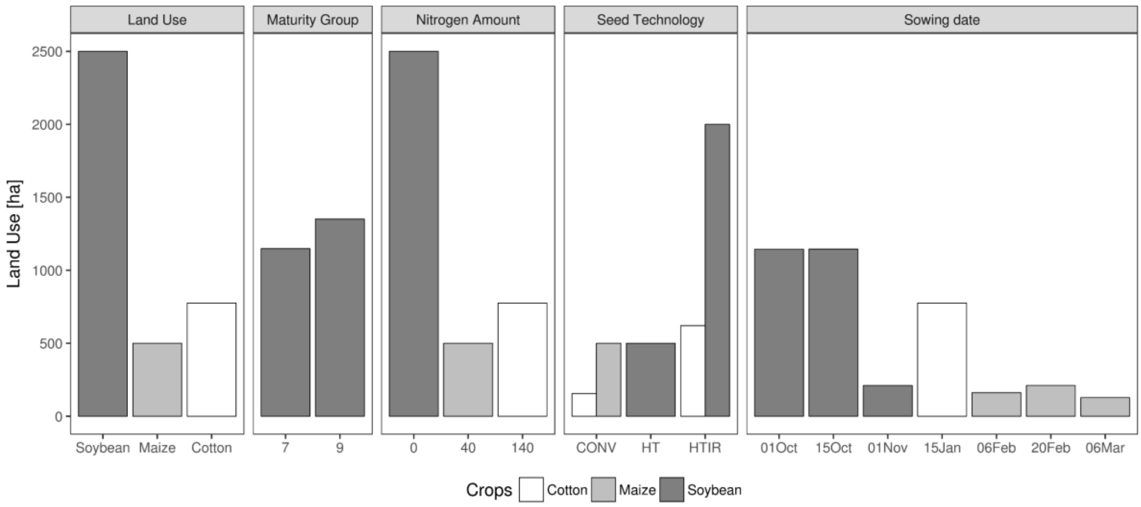

Figure 2.8 *Optimal land use simulated by MPMAS to a typical farm in South Central region. Seed technology: conventional (CONV), herbicide tolerant (HT), herbicide tolerant and insect resistance (HTIR).*

In order to sow maize and cotton in the second season, the agent shall start by sowing soybean MG7 to achieve higher yields on the second season. Afterwards, the agent can sow soybean MG9, as soybean with a longer maturity cycle achieves higher yields (Figure 2.5). Other decision variables, such as nitrogen amount and seed technology are also simulated for each crop and represented in Figure 2.8.

Even though soybean MG9 achieves higher yields, one should consider the trade-off between yields and sowing dates for the second season crops, as those combinations are intrinsically linked to the length of the soybean's maturity cycle. In this way, the yield difference from shorter maturity cycles shall be offset by a yield gain on the second season. These results confirm the findings of Allen and Lueck (1998), where the authors argue that the steps of linking the production cycle and field activities are a key element to technology diffusion. It is important to note that each farm will have its own optimal solution, as it is subject to environmental conditions and production factor endowments (such as land, machinery, labor and capital). Therefore, Figure 2.8 represents the optimal solution for only one specific farm holding and, therefore, should not be considered in a different context.

2.5. Conclusions

The results of our simulation suggest that climatic conditions play a major role in Mato Grosso's agricultural production, and there is a wide range of variation in crop yields across the state. Early sowing dates are an important variable for achieving higher yields in the second season and our simulation experiment fully capture the yield difference between those sowing dates on maize and cotton production, providing key elements and insights to a farmer's decision-making process. The closer a crop is sown to the beginning of the rainy season, the higher the probability to achieve greater yields, as the crop is exposed to less water deficit, which can be decisive, especially in years of low price levels or higher production costs. Furthermore, high levels of incoming solar radiation at the beginning of the year (Jan-Feb) favor carbon assimilation and hence yield formation.

As soybean is sown at the beginning of the rainy season, sowing date is not such a decisive decision variable as for second season maize and cotton. However, sowing dates are closely linked to the choice of suitable soybean maturity groups. A longer growing cycle means a higher yield because the crop has more time to develop. However, adopting a longer maturity cycle reduces farmer's second season options and, as discussed above, the short cycle soybeans that are sown first allow a higher yield during the second season cropping system. In this context, the interdependence between the elements which define the production system also determines a certain level of rigidity. Therefore, the flexibility that soybean MG7 produces in the cropping system is a key element to those farm holdings.

In conclusion, we argue that the introduction of short maturing soybean varieties increased farmers' flexibility in second season crop planning, but at the same time also increased the production system's complexity as well as trade-offs in crop yields, corroborating the use of an Integrated Assessment approach. We showed that our simulation experiment has the full potential of assessing region-specific decision variables which farmers have to deal with in Mato Grosso. Our model provided key information to farmer's decision-making process, stressing the most important decisions and its implication to the whole system, as well for its economic performance. Our simulation experiment showed that all decision variables are somehow connected and pointed out the importance of evaluating site-specific and/or region-specific variables.

Chapter 3. Integrated assessment of novel two-season production systems in Mato Grosso, Brazil

Marcelo Carauta, Affonso Libera, Evgeny Latynskiy, Anna Hampf, José Maria Ferreira Jardim da Silveira, Thomas Berger

This this chapter has been published[5] in the Proceedings of the 8th International Congress on Environmental Modelling and Software in July, 2016.

Abstract

One of the most significant advantages of growing crops in Mato Grosso (in mid-western Brazil) is that farmers can grow two crops (in some specific cases even three) in the same season. From an economic point of view, this provides a substantial comparative advantage. On the other hand, it increases the number of decision variables a decision-making agent has to take into account. The agricultural production planning is complex and dynamic, and it needs to consider crop rotation/succession in accordance with the annual variability of climatic conditions. We developed a region-specific bio-economic micro-simulation model to assess the trade-offs between soybean, maize and cotton production in that region. The model explicitly accounts for a combination of several variables, such as crop rotation (between seasons and years), planting dates, fertilizer requirements, crop varieties, soybean maturity groups, climatic conditions, and prices. The simulation was implemented in MPMAS, a multi-agent software package developed for simulating the farm-based economic behavior and human-environment interactions in agriculture. Crop yields were simulated with the Model of Nitrogen and Carbon dynamics in Agro-ecosystems (MONICA). The simulation captured inter-regional differences between farm holdings, which is one of the key factors to assess technological diffusion over time in large and diverse regions, such as Mato Grosso. The simulation results show that the introduction of soybean varieties of maturity group VII

[5] Carauta, M., Libera, A.A.D., Latynskiy, E., Hampf, A., Silveira, José Maria F. J., Berger, T., 2016. Integrated assessment of novel two-season production systems in Mato Grosso, Brazil, in: Proceedings of the 8th International Congress on Environmental Modelling and Software. 8th International Congress on Environmental Modelling and Software, Toulouse, France.

increased farmers' flexibility, providing a more significant number of crop rotation possibilities. It exhibits a trade-off effect between maize and cotton cultivation, as both crops compete for the area during the second season, changing the production system set-up in that region.

3.1. Introduction

Brazil is one of the leading countries in the agricultural world market, and the state of Mato Grosso is the most important internal contributor, accounting for 24% of national grain production (Brazilian National Supply Company 2016b). Currently, Mato Grosso leads the production of soybean, maize, cotton, sunflower and holds the largest cattle herd in the country (Brazilian National Supply Company 2016b). According to the Brazilian Institute of Geography and Statistics (IBGE), the state is the third largest by area (Brazilian Institute of Geography and Statistics 2015). It is in the western part of the country and presents three different ecosystems: Cerrado (Brazilian Savanna`s), Pantanal (wetland) and the Amazon Rainforest.

An important factor that distinguishes this region from others is the possibility of growing more than one crop per season. The first season begins with the onset of the rainy season in mid-September, whereas the second season lasts from mid-January until July-August. This factor brings several advantages such as the reduction of fixed costs, new revenue possibilities, and increased use of production factors (i.e.: land, labor, and capital). This technological progress completely changed the Brazilian production system. Nowadays, maize production during the second season accounts for 66% of the national maize production, whereas two decades ago it was only 11% (Brazilian Institute of Geography and Statistics 2018). The second production season in Mato Grosso has become as important as the first one.

This double-cropping process led to a production intensification, allowing farmers to produce more on the same cultivated area. Over the last ten years, grain production in Brazil has grown by 72% while cultivated area expanded by 22%. This production increase was mostly led by yield increases, which grew 41% over that period (Brazilian National Supply Company 2016b). The economic viability of agricultural enterprises in Mato Grosso is based on technological advances, which provide the necessary incentives for the development of those activities. The main technological advances were the establishment of a new technical paradigm (Dosi 1982) in the local agricultural sector (mainly GMOs - genetically modified organisms – and short maturity cycle seeds) combined with the expansion of the agricultural frontier due to the adaptation of new seeds to local conditions. The innovation went through changes over time, receiving incremental improvements, which also determined changes in its performance. This process was later revealed to be a complex issue because of the uncertainty related to technological diffusion process in a double-crop production system.

The objective of this study is to investigate how the introduction of early maturing soybean varieties (MG VII) influences the economic organization of farms in the Brazilian Midwest. Therefore, this article addresses the decision variables farmers need to take into consideration when tackling the trade-off between first and second production season ("*safra*" vs. "*safrinha*"). As a research hypothesis, we argue that the main aspect which influences farmers' technology adoption is related to an increase in flexibility regarding crop management under extreme climate conditions (interaction between climate and pest occurrence).

By conducting a quantitative analysis in a farm level approach of the farm systems in Mato Grosso, we developed a region-specific bio-economic micro-simulation model which is able to capture the interregional differences between farms, farm-based economic behavior and human-environment interactions in agriculture. Our multi-agent application allows us to evaluate farm agent interactions as well as technology diffusion at the farm and macro level (Mato Grosso State). The simulation results provide detailed information on how the production system changed with the introduction of a new soybean cultivar as well as the trade-off between first and second production season.

3.2. Materials and methods

3.2.1. Methodology

We applied an integrated assessment (IA) based on a multi-agent micro-simulation model to assess the adoption of early maturing soybean varieties (maturity group VII) on the agricultural production system in Mato Grosso. IA can be defined as an interdisciplinary process which combines knowledge from diverse scientific disciplines in order to allow for a better understanding of a complex system or phenomena (van Ittersum et al. 2008). Our IA approach offers several advances when compared to traditional economic analysis. First, it considers the cross-scale issue, as the farm-based multi-agent system enables us to simulate the heterogeneous population of real-world farms. In that way, it is easy to up-scale farm level data into different macro levels (i.e. market, sector, municipalities, states or regions). Second, it enables the assessment of policies, e.g. ABC Program (Brazilian low carbon agriculture program) (Carauta et al. 2017a), that evolve both the micro and macro level (van Ittersum et al. 2008). Third, the multi-agent micro-simulation component generates mathematical programming problems which take many operation and investment constraints of individual farm holdings into account. Because of technical advances in computational processing, it can be easily extended to all farms and agents of the study area, allowing the analysis of different groups of agents and/or farms. Fourth, the interdisciplinary approach connects the socio-economic component with the biophysical component. The crop growth model simulates the effect of different soil types, climatic conditions, and crop management practices on crop yields. Additionally, our multi-agent application takes farm agent interactions into account, and, therefore, enables the assessment of technological innovations. Finally, the model dynamics are suitable to assess long-term impacts of climate, soil conditions and farm production factors.

The simulations were carried out with MPMAS (Mathematical Programming-based Multi-Agent Systems), a multi-agent software package for simulating land use change in agriculture. MPMAS uses the constrained optimization approach to simulate a farm decision-making process in agricultural systems (Schreinemachers and Berger 2011). This software has been applied in many studies of IA of the farm-level agricultural production system and on innovation diffusion in agriculture (Arnold et al. 2015; Berger et al. 2015; Troost et al. 2015; Wossen and Berger 2015).

The crop yields were simulated with the MONICA model, a dynamic, process-based simulation model which describes transport and bio-chemical turn-over of carbon, nitrogen, and water in agro-ecosystems (Nendel et al. 2011). Both software packages are linked through an online database stored in a MySQL server. The crop yields are simulated for all climate conditions and region-specific characteristics and stored in the database. Then, the database application MPMASQL accesses all relevant information in the database and converts it to an MPMAS input. Finally, MPMAS is integrated into a computer cluster with the use of COIN`s CBC mixed-integer programming solver, specifically calibrated for this study. A full description of MPMAS features can be found at Schreinemachers and Berger (2011).

Each farm agent faces two decision problems in each simulation period, which corresponds to one agricultural year: an investment decision and a production decision. Those problems are converted into a MILP (Mixed Integer Linear Programming model). The full MP-optimization problem for each agent consists of 4023 decision variables (165 integers) and 4002 constraints, which results in a substantial number of choices regarding the crop production system, crop management, crop rotation, production factor requirements (acquisition of inputs, labor, and machinery). Agents in MPMAS maximize expected farm income, which needs to be done subject to a set of constraints (such as land, machinery capacity, labor supply and capital), specified in the form of equations or inequalities.

The interaction between agents was done through a technology diffusion component. Agent interactions are implemented as a frequency-dependent contagion effect: the more agents adopt a technology, the more it becomes accessible to others. Agents were divided into five categories (innovators, early adopters, early majority, late majority, and laggards) according to the classification and methods described by Rogers (1995). To fully capture the technological diffusion process, the simulations were run for six years. In our approach, we considered early maturing soybean (MG VII) as technological innovation.

A crop calendar of agricultural activities was created to capture the timing of agricultural activities and, therefore, correctly simulate farm resource allocation over time, such as machinery and labor. The crop calendar was created according to the local technical recommendation on which agricultural activities are typically undertaken for each of the crops included in the model. The link between the crop calendar and the data on labor and machinery provides estimates of weekly machinery and labor requirements. The crop calendar is also linked to MONICA model, that simulates crop growth based on weather data in a daily time resolution.

3.2.2. Model Parameterization

The MPMAS model was parametrized for five municipalities in Mato Grosso: Campo Novo dos Parecis, Sinop, Campo Verde, Tangará da Serra and Canarana. According to Instituto Mato-Grossense de Economia Agropecuária (2010b), these municipalities are representative of the following macro regions: West, Mid-North, Southeast, South Central and Northeast. The agent population includes all crop-producing farm holdings which are larger than 50 hectares, according to the latest agricultural census available (Brazilian Institute of Geography and Statistics 2006). At that time, there were 720 farm holdings which correspond to 74% in terms of number and 99% regarding the cultivated area of all crop-producing farms in those municipalities. Based on these data, a statistically consistent population of model agents was set up, following the Monte Carlo approach as described by Berger and Schreinemachers (2006).

The MONICA model was calibrated using data from different field experiments (Aguiar and Guiscem; Fundação de Pesquisa e Desenvolvimento Tecnológico Rio Verde 2013; Rosolem 2001). Soil classes were assigned to each model agent based on the official maps of socio-ecological zoning provided by the Mato Grosso State Secretary of Planning (Secretaria de Estado de Planejamento e Coordenação Geral de Mato Grosso 2011). Soil classes in each municipality were also linked with MONICA to simulate crop yields. We further implemented a weather data set from 1999 to 2013 for each of the five model regions. These data were taken from the website of the Brazilian Meteorological Institute (Instituto Nacional de Meteorologia 2015) and contain the following weather data in a daily time resolution: maximum and minimum air temperature, sun duration, precipitation, wind speed and relative air humidity.

The estimation of production costs for each crop and region is done on site for those five municipalities and refers to the cropping season of 2015/2016 (Instituto Mato-Grossense de Economia Agropecuária 2016a). The production cost was estimated with a collaborative approach in which farmers and experts from all stages of the production chain (i.e.: input sellers, machinery dealers, rural union) were involved. The estimation was done for “modal farms” - a productive unit with characteristics that approximate the local reality profile to the regional (Brazilian National Supply Company 2010). Furthermore, region-specific data on the capital requirement, funding sources and credit demand, crop management, machinery, and labor capacity, as well as farm endowments, were estimated. In addition to production cost, we also estimated post-harvest costs related to transportation, storage, processing, and taxes. The price time series data for agricultural products were taken from the IMEA online price dataset (Instituto Mato-Grossense de Economia Agropecuária 2015).

The agricultural production practices included in MPMAS refer to the most common agricultural commodities cultivated in the selected macro-regions of Mato Grosso: soybean, maize, and cotton. Our simulation models MPMAS and MONICA also include region-specific production practices (for example, agents in different regions employ different types of pesticides and choose the different intensity of machinery use, etc.). For soybean, we considered three maturity cycles (MG VII, MG VIII, and MG IX corresponding to less than 115, between 115 and 126 and greater than 126 days of maturity, respectively); four planting dates (01-Oct, 15-Oct, 01-Nov and 15-Nov) and three technologies (Conventional - CONV -, Herbicide Tolerant - HT - and Herbicide-Tolerant and Insect Resistant -HTIR). For maize and cotton, instead of the maturity cycle, we introduced different amounts of nitrogen application as a decision variable. Consequently, four planting dates for maize (20-Jan, 06-Feb, 20-Feb, and 06-Mar); five nitrogen applications (0, 40, 80, 120 and 160 kg/ha) and three technologies (CONV, IR, and HTIR) were considered for maize. Finally, for cotton, five planting dates, two in the first season (15-Dec and 30-Dec) and three in the second season (15-Jan, 30-Jan and 15-Feb), as well as seven nitrogen levels (0, 90, 140, 185, 230, 280 and 450 kg/ha) and four technologies (CONV, HT, IR and HTIR) were considered.

Different crop management regimes for each agricultural production practice were also taken into account. Crops with longer maturity cycles require more fungicide and insecticide applications; Insect Resistant (IR) crops require fewer insecticides applications; Herbicide Tolerant (HT) crops require herbicides with different active ingredients and, specifically for soybean HTIR, as longer the maturity cycle, the greater is the substitution effect between the insecticide application and the genetically modified (GM) Bt toxin. The crop management options for MPMAS were defined in accordance to a farm-level survey from Céleres – a local agribusiness consulting enterprise – including 157, 299 and 303 observations for soybean, maize, and cotton, respectively, as well as technical advice from local experts.

3.2.3. Model Validation

In order to assess to which extent our combined MPMAS-MONICA simulations are a good representation of real-world observations, we applied an empirical validation in which the output of our economic microsimulation model was compared to the corresponding statistics from the real world (Fagiolo et al. 2007). For our IA approach, we used a three-step process, one for the biophysical model component and two for the bio-economic model component. The first step was the validation of the output of the crop growth model MONICA. The validation process considered Mato Grosso`s soil and climatic conditions and used municipal crop yield estimations from Brazilian Institute of Geography and Statistics (2016a). We used three different statistical indices to assess the model´s performance: Mean absolute error (MAE), root mean square error (RMSE) and Willmott´s index of agreement (WIA), a standardized measure of the degree of model prediction error. The validation of the crop growth model suggests that its predictions match both with the municipality level average yields and with the yield responses due to different climate conditions over the years (MAE of 322.05; 835.67; 519.94; RMSE of 388.67; 1076.29; 667; WIA of 0.68, 0.72 and 0.67 for soybean, maize, and cotton, respectively). Due to lack of farm-level information on individual crop yield and management, it was not possible to validate the simulated yield at the farm agent level.

The second and third steps are related to the validation of our bio-economic model component, which was done with the MPMAS software. First, we ran a farm level validation and after that, a municipality level validation. Those two processes were carried out separately and were necessary because the model simulates both the behavior of individual farms and the study area. For the farm level validation, data from the Mato Grossense Institute of Agricultural Economics (Instituto Mato-Grossense de Economia Agropecuária 2013a) was collected and, for the municipality level, municipality land use data from Brazilian Institute of Geography and Statistics (2006). The validation considered the different farm profiles for each region, such as land ownership, asset endowments, as well as the inter-regional characteristics and constraints.

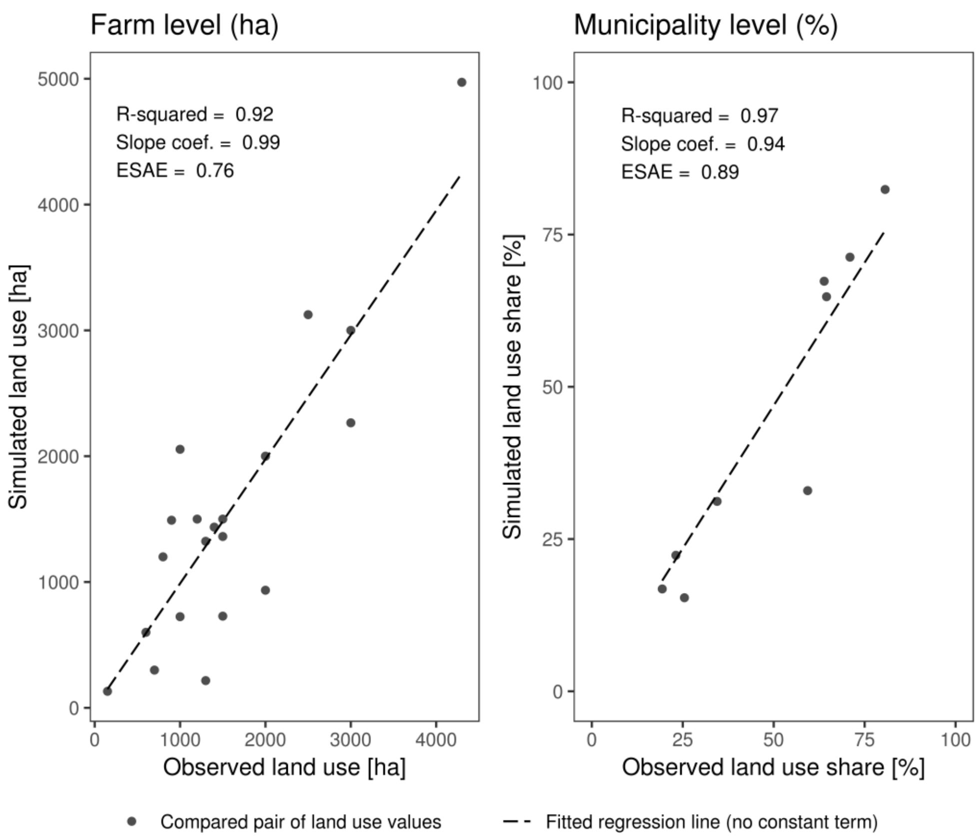

Figure 3.1 *MPMAS model validation*

The model efficiency was estimated based on standardized absolute errors (ESAE). At the farm-level, our application has a model efficiency of 0.76, which improved to 0.89 at the municipality level (Figure 3.1). Besides, the fitted no-constant regression lines and their calculated R-squared (0.92 for the farm level and 0.97 for the municipality level) indicates a good fit of the model results. Therefore, the validation outcomes suggest that our MPMAS application can simulate land use decisions consistently and accurately both at farm and municipality level.

3.2.4. Experimental Set Up

To assess the impact of the introduction of early maturing soybean varieties (MG VII) on the agricultural production systems in Mato Grosso, we compared a baseline scenario (reflecting the current conditions) with a counterfactual scenario where no soybean varieties of maturity group VII are available. In the counterfactual scenario, farmers face a more restricted set of double crop combinations, because a longer soybean cycle reduces the sowing date possibilities for the second season.

The technology diffusion was simulated in a third scenario using a two-step approach originally developed by Berger (2001). During the first step, MPMAS evaluates whether a certain adoption threshold has been reached, while the second step allows model agents to adopt soybean MG VII if they were given access during the first step. The simulated results from this scenario were then compared to the baseline (full access for all agents to innovation immediately) and the counterfactual scenario (scenario without technological change).

Furthermore, we designed four scenarios with alternative market conditions, in which maize (M.P.) and cotton prices (C.P.) were increased by 15 and 30 percent. The purpose of those scenarios is to assess the farmers' decision making regarding second season crops (in which maize and cotton compete for the area) as well as the sensitivity of the production system organization due to changes in crop prices.

3.3. Results and discussion

3.3.1. The importance of early sowing dates

Figure 3.2 shows MONICA's simulated crop yields from 2000 to 2013 for soybean, maize, and cotton about maturity group and sowing date (yields were averaged for modal agricultural practices). As Figure 3.2 shows, early maturing soybean varieties exhibit, on average, lower yield in comparison with MG VIII and IV. On the other hand, its adoption enables farmers to sow cotton and maize at early sowing dates, increasing the number of crop rotation combinations. Before the introduction of soybean MG VII, farm agents had five possible combinations for the cover-crop-cotton production system and four for the soybean-cotton crop rotation. The diffusion of this novel technology increased the number of possible combinations to thirteen in the soybean-cotton production system, allowing for an additional sowing date for cotton in the second season (15-Jan). The MONICA simulations suggest that both maize and cotton present greater yields at early planting dates, which were not achievable before the introduction of soybean MG VII. Figure 3.2 also shows that maize and cotton have lower yield variability (or crop yield risk due to climate conditions) when planted at early sowing dates since there is less probability of crops facing a *veranico* (drought during sensitive crop development stage).

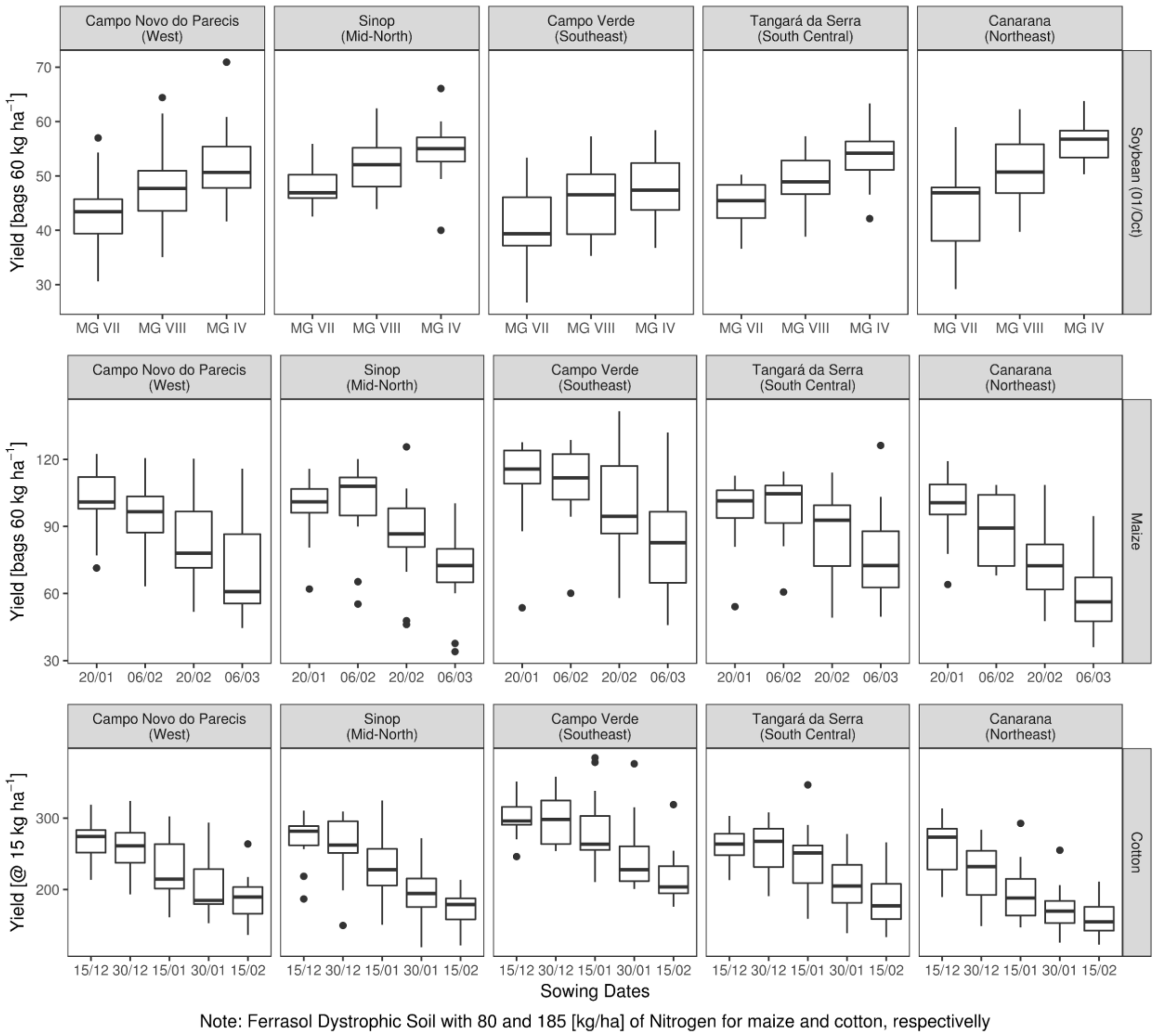

Figure 3.2 *Simulated crop yields for modal agricultural practices (simulated years: 2000-2013).*

In regard to maize cultivation, our IA simulation suggests that the shortening of soybean cycle leads to a lengthening of the maize sowing window, shifting part of the cultivation to the earliest sowing dates (Figure 3.3), which indicates a positive crop yield trade-off between those technologies, suggesting a better economic performance in terms of farm gross margin (since the yield decrease due to adopting soybean MG VII is compensated by a cotton/maize yield increase at early sowing dates). Moreover, it allows a better distribution of production activities over time, increasing farm flexibility regarding both crop and farm management and reducing periods of intensive use of labor and machinery. Furthermore, since the sowing date of maize has a direct impact on yield (Figure 3.2), it becomes an important variable for defining crop technological level (such as seed variety and fertilization amounts).

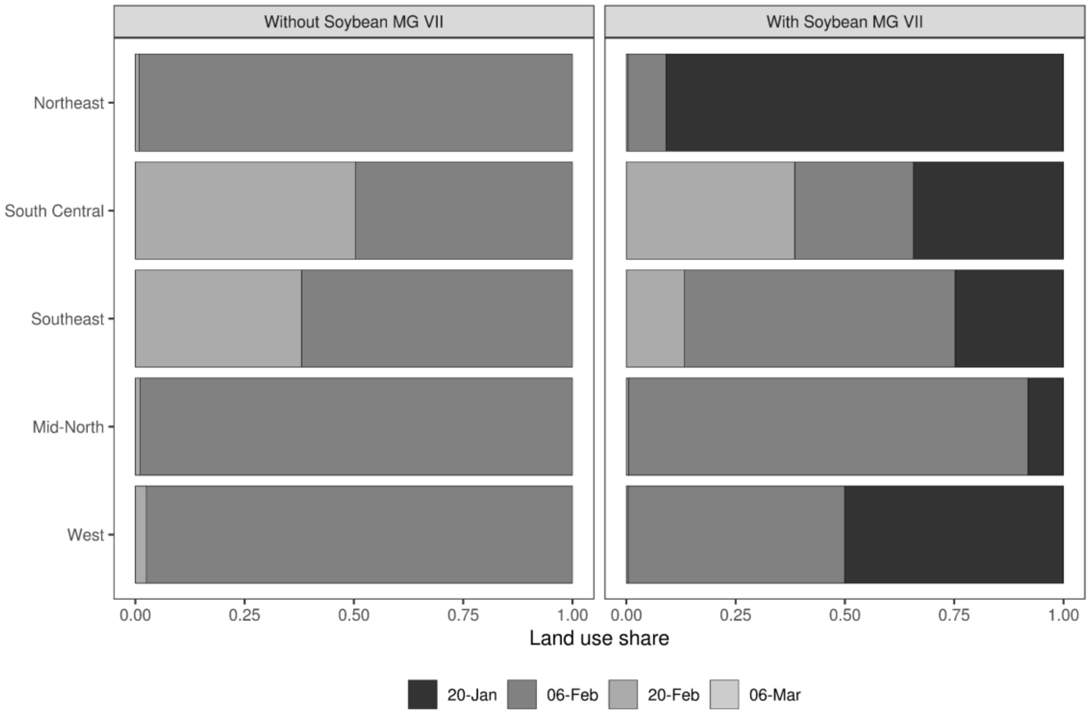

Figure 3.3 *Simulated maize land use*

3.3.2. Economic impact of soybean MG VII adoption on farm income

Figure 3.4 depicts the simulated impact of soybean MG VII adoption on farm income between both scenarios (with and without soybean MG VII). Agents are ranked by their average farm income per hectare in the scenario without soybean MG VII. Our simulation indicates a positive effect of technology adoption. Agents of almost all farm sizes categories benefited from the novel technology and increased their income.

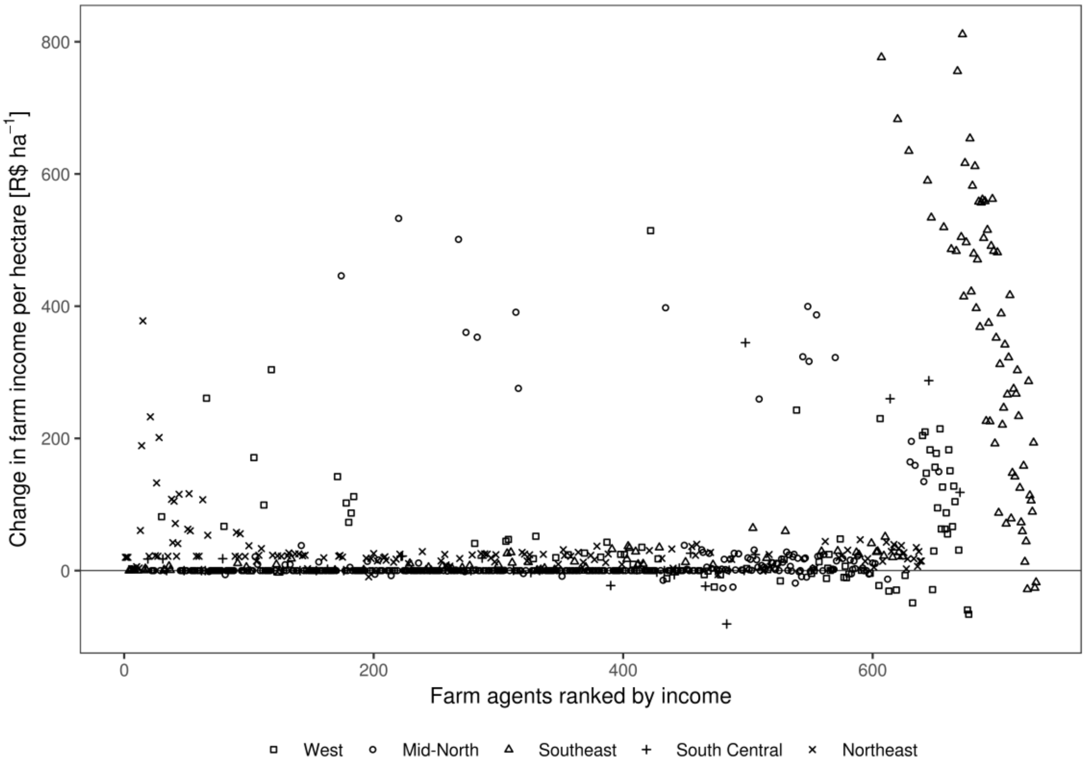

Figure 3.4 *Income change in the baseline [With Soybean MG VII] compared to counterfactual scenario [Without Soybean MG VII]. Individual agent incomes were ranked by income in the counterfactual scenario.*

3.3.3. Second season (*safrinha*) trade-offs

The introduction of soybean MG VII amplified the maize sowing window and allowed farm agents to achieve higher yields (as shown in Figure 3.1). Moreover, it favored the soybean-cotton double crop rotation, allowing farm agents to obtain a higher income per hectare. As maize and cotton compete for the area in the second season, the net effect remains uncertain. Therefore, we developed a price sensitivity analysis for both crops that allows us to fully assess the second season trade-off between maize and cotton (Figure 3.5).

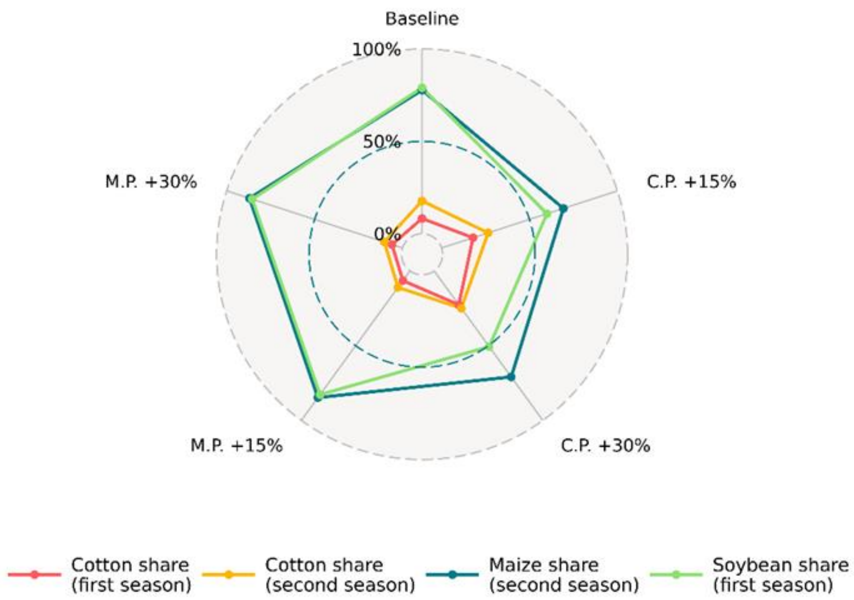

Figure 3.5 *Price sensitivity analysis of maize vs. cotton*

While there was a higher share of second season cotton (18%) compared to first season cotton (8%) in the baseline scenario, Figure 3.5 shows that as soon as cotton price increases, the share of first season cotton increases too, since it has the potential to achieve higher yields, in comparison to cotton sown at late sowing dates. Cotton becomes more profitable thus agents change from soybean-cotton to cover crop-cotton system. On the other hand, when maize prices increase, agents start to grow more maize, which in turn increases the soybean share. As cotton competes with soybean for the area in the first season, a decrease of first season cotton is observed in that scenario.

3.4. Conclusions

This study reports the development of a multi-agent bio-economic model to assess the impact of technology adoption on complex agricultural production systems, such as the double cropping system in Mato Grosso. Rather than estimating a specific land use, we focused on developing an integrated assessment approach which considers: farm heterogeneity (such as farm endowments, land ownership and land use), agent interactions (technology adoption), environmental conditions (such as soil properties and climate conditions), a large number of agricultural practices (taking into consideration different seed varieties, sowing dates and nitrogen amounts), and region-specific characteristics (such as prices and socio-economic characteristics).

Our model application in Mato Grosso suggests that the introduction of early maturing soybean varieties (MG VII) completely changed the optimal set of the double crop rotation system currently adopted by farmers in Mato Grosso. Interestingly, our simulations show that the introduction of this new soybean cultivar had a more significant impact on maize and cotton production than on soybean cultivation itself. It happened because a shorter soybean cycle increased the number of crop rotation possibilities during the first and second season, generating a trade-off effect between maize and cotton cultivation. Despite its lower yields (when compared with MG VIII and IX), farmers adopted early soybeans varieties aiming to achieve higher crop yields during the second season. Our result shows that this trade-off is positive and higher farm income is possible after the adoption of this technology.

Regarding maize, our simulation showed a shift of optimal sowing dates to the first two dates (20-Jan and 06-Feb), which have the potential to achieve higher yields and run lower climate risk. For cotton cultivation, it was shown that farm agents switch from cover crop-cotton to soybean-cotton production system when soybean MG VII is being adopted, as the latter enables them to achieve a higher income per hectare, as well as diversifying their production.

Besides, the introduction of soybean MG VII also allowed farm agents to produce more on the same area. A comparison of the baseline and the counterfactual scenario allows us to infer that the cultivated area in the second season would be lower in the absence of that technology. By enabling farm agents to produce more in the second season, a shorter soybean cycle leads to intensified land use and higher production levels using the same cultivated area. The increased number of crop rotation combinations also allowed farm agents to distribute their production activities over time.

Even though soybean with shorter production cycle exhibits, on average, lower yields when compared to late maturing varieties, they are still preferred by farm agents in our simulation because they enable them to increase cultivation in the second season, by extending the maize sowing window and by increasing cultivation possibilities of soybean-cotton rotation systems.

Chapter 4. The biophysical and socio-economic dimension of yield gaps in the Southern Amazon – a bio-economic modelling approach

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This chapter has been published[6] in Agricultural Systems in May, 2018.

Abstract

Farmers in the State of Mato Grosso are among Brazil´s most productive soybean, maize and cotton producers, but are still far away from achieving potential yields as measured on experimental sites. The objective of this study was to decompose yield gaps in the Southern Amazon into their biophysical and socio-economic dimensions. To achieve this, the process-based Model of Nitrogen and Carbon dynamics in Agro-ecosystems (MONICA) was coupled with the Mathematical Programming-based Multi-Agent Systems (MPMAS) software. Soybean, maize and cotton yield gaps were simulated for five macro-regions in Mato Grosso considering different climatic, edaphic and crop management conditions. The impact of socio-economic constraints on crop yields was assessed in form of full factorial design in which each factor was set to a baseline and unconstrained level. The simulation results show that biophysical yield gaps (due to water and nutrient deficit) account for 24% of potential yields (Y_p), whereas an unrestricted access to machinery, labor, credit and technological innovation would lead to a reduction of yield gaps by 6.1% and an expansion of cropland by 22%. Yield gaps can be reduced through improved water- and nutrient management, appropriate cultivar-sowing date combinations and in part by a removal of socio-economic constraints. However, each solution comes with its own limitation either in form of increased pressure on limited environmental resources or incompatibility with individual farmer objectives. Future yield gap

[6] Hampf, A.C., Carauta, M., Latynskiy, E., Libera, A.A.D., Monteiro, L., Sentelhas, P.C., Troost, C., Berger, T., Nendel, C., 2018. The biophysical and socio-economic dimension of yield gaps in the southern Amazon – A bio-economic modelling approach. Agricultural Systems 165, 1–13. 10.1016/j.agsy.2018.05.009.

closure will depend on the access to arable land, environmental regulations preventing further deforestation as well as political and economic incentives for sustainable intensification.

4.1. Introduction

The agricultural sector faces immense challenges: it is confronted with the task of producing sufficient food and biomass for an increasing world population and the conservation of natural resources on which it depends on (Food and Agricultural Organization of the United Nations 2009; United Nations, Department of Economic and Social Affairs, Population Division 2015) . Currently, it is responsible for one quarter of global greenhouse gas emissions (Intergovernmental Panel on Climate Change 2014) and contributes to the loss of biodiversity through cropland expansion and the degradation of soil and water resources through an excessive use of fertilizers and pesticides (Tilman et al. 2011). Foley et al. (2011)found that global food production can be increased by 2.3 billion tones if the gap between potential yields (Y_p) and actual yields (Y_a) was closed to 95%. According to Mueller et al. (2012), large production increases (45% to 70%) will be possible through yield gap closure if nutrient imbalances and inefficiencies are reduced. However, the scope for further yield gap reductions varies from region to region: while farmers in Western Europe, the United States, China and South America are close to attain Y_p, farmers in Eastern Europe and Sub-Saharan Africa face large intensification opportunities as those are the regions with the largest yield gaps (Licker et al. 2010; Mueller et al. 2012).

Over the past two decades, Brazil has emerged as a global player on the agricultural world market and is nowadays leading the exportation of soybean, corn, sugar, meat, coffee and ethanol (International Monetary Fund 2017). Large parts of Brazil´s agricultural commodities are produced in the state of Mato Grosso (MT) in the Southern Amazon (Brazilian National Supply Company 2016b), where intensive double-cropping systems were adapted to local climatic conditions (Arvor et al. 2014). However, with about one third of the total deforested area in the Legal Amazon (Instituto Nacional de Pesquisas Espaciais 2017), MT is also a hotspot of deforestation. Despite recent intensification processes and technological advances, farmers in the state of MT are still far away from obtaining yield potentials as measured on experimental sites. Between 1987 and 2013, the average maize yield obtained on experimental sites of the Brazilian Agricultural Research Corporation (Brazilian Agricultural Research Corporation 2016) in Central-West Brazil was 53% higher than the average maize yield reported by farmers in MT (Brazilian Institute of Geography and Statistics 2018). In a study on soybean yield gaps in Brazil, Sentelhas et al. (2015) found that the yield gap (Y_g) between

Y_p and actual yields (Y_a) in two locations in MT amounts to 1.2 t ha^{-1}, corresponding to 27%, and is mainly caused by water deficit and low soil fertility.

Biophysical and management related factors of yield gaps have been studied at the local (Soltani et al. 2016; Stuart et al. 2016), regional (Grassini et al. 2015; Henderson et al. 2016; Monteiro and Sentelhas 2013) and global (Foley et al. 2011; Licker et al. 2010; Mueller et al. 2012; Neumann et al. 2010) scale. A comprehensive ongoing research project on yield gaps is the Global Yield Gap and Water-Productivity Atlas (GYGA) that aims at providing estimates of exploitable yield gaps for all major food crops and countries. While time-intensive and costly field experiments have been used in the past to assess the magnitude and possible causes of Y_g, nowadays, crop simulation models provide flexible tools to simulate the effects of interacting constraints on yields (Affholder et al. 2003; Boling et al. 2010). Suboptimal nutrient and water management, inappropriate sowing dates, insufficient crop protection and low soil fertility were identified as key biophysical and management related factors explaining the yield gap (Beza et al. 2016).

The relation of socio-economic factors to yield gaps is less straight forward. According to Penning-de-Vries (1990), socio-economic factors never interact directly with plant growth, but constitute important boundary conditions, which determine farmers' decision-making process and hence the management choices they make. The price of fertilizers, for example, is not directly linked to crop growth, but defines how much fertilizer is applied, particularly if input costs are high. Limited access to credit, machinery and transportation costs, labor shortage, risk aversion, poor infrastructure, insecure land tenure rights, adverse land management policies and political instability are some of the major socio-economic and institutional hurdles of yield gap closure (Duwayri et al. 2000; Liu et al. 2016; Lobell et al. 2009; Mueller et al. 2012; van Dijk et al. 2012; van Dijk et al. 2017; Zhang et al. 2016).

In a review on yield-gap explaining factors, Beza et al. (2016)found that biophysical factors are more often considered in yield gap analysis than farm characteristics or socio-economic factors, but the latter often explain large parts of the yield gap. Yield gap studies that address both the biophysical and socio-economic dimension of yield gaps are scarce as well as yield gap studies for the Southern Amazon. We seek to address this research gap by decomposing the yield gap in the Southern Amazon into its biophysical and socio-economic dimensions. The objectives of this study are to

(i) simulate potential, water-limited and actual soybean, maize and cotton yields in response to different climatic conditions, soil types, sowing dates, crop rotation schemes and fertilization rates in five survey sites in MT;

(ii) estimate the magnitude of the biophysical yield gap in MT and identify its explaining factors;

(iii) assess the main effects of socio-economic constraints on yields in MT.

Yield gaps were decomposed into their biophysical and socio-economic components by coupling the process-based Model of Nitrogen and Carbon dynamics in Agro-ecosystems (MONICA) with the Mathematical Programming-based Multi-Agent Systems (MPMAS) software, which simulates decision-making at the farm household level (Nendel et al. 2011; Schreinemachers and Berger 2011). Coupling two simulation models from different disciplines (agronomy and agricultural economics) helps to "improve results, raise the number of alternatives for management […] and expand area to which the new model is applicable" (Penning-de-Vries 1990). In fact, neither crop growth nor agro-economic models alone can adequately explore the full dimension of yield gaps: While crop models find it difficult to represent farmers` decisions regarding the use of purchased inputs, agro-economic models fail to capture how biophysical determinants affect yield levels (Schreinemachers et al. 2007; Vera-Diaz et al. 2008). The integrated MONICA and MPMAS model system allows for a detailed representation of crop growth under different climatic and crop management conditions as well as the assessment of socio-economic constraints on farm household decision making. This interdisciplinary approach enables us to address a much larger range of yield gaps-related determinants than common disciplinary approaches can do.

4.2. Material and methods

4.2.1. The MONICA model

MONICA is a process-based crop growth model that was initially developed to account for the combined effects of changing climate variables and soil processes in Central Europe (Nendel et al. 2011; Nendel et al. 2014). It consists of several interrelated modules that can simulate crop growth, soil hydrology and temperature, nitrogen uptake and organic matter turnover in the soil. The crop growth process is simulated as a function of temperature, solar radiation and atmospheric CO_2 concentration. In a simplified process of photosynthesis, light energy is converted into carbohydrate molecules, which, in turn, are distributed among crop organs (root, shoot, leaf and fruit), while the plant evolves through several development stages from sowing to harvest maturity. In early development stages, root and leaf growth is fostered, whereas shoot and fruit growth is enhanced in later development stages. The duration of each development stage depends on the number of growing degree days (GDD), which are calculated as the difference between daily average temperature and a crop-specific base temperature (Nendel et al. 2014).

MONICA has been widely tested and benchmarked in international model inter-comparisons, including simulations of maize (Durand et al. 2017) and soybean (Battisti et al. 2017a; Battisti et al. 2017b) and their response to climate factors and management. These tests included soil (pseudo-sand aggregated ferrosols) and climate environments (hot and humid winters, warm and dry summers) that are comparable to the conditions in MT. MONICA considers the sand-like water transport alongside the micro-aggregates, while reproducing the water storage behavior of the clay aggregates, as it is typical for ferrosols in this region. However, soil surface charge-induced deviations from standard temperate nitrate and ammonia transport formalisms, as could be expected for tropical acid soils, are not implemented in MONICA. Also, as MONICA considers only nitrate uptake in plants and not ammonia, the typically elevated ammonia-to-nitrate ratio in tropical soils may be a factor that attenuates MONICA's ability to reproduce N response of crops in tropical environments. Within the scope of the German-Brazilian research project Carbiocial (Carbon Sequestration, Biodiversity and Social Structures in the Southern Amazon), MONICA was calibrated to crop cultivars grown in a sub-tropical environment (Carauta et al. 2017a; Carauta et al. 2017b; Sociedade Brasileira de Economia, Administração e Sociologia Rural 2016). An evaluation of the predictive performance of MONICA at farm-level is shown in the supplementary material.

4.2.2. MPMAS software

MPMAS is a software package for dynamic modelling of agricultural holdings, which are represented by computational agents (Schreinemachers and Berger 2011). For modelling farm investment, production and consumption decisions, MPMAS employs mathematical programming (MP), an optimization method originating from operations research. Agents in MPMAS maximize expected farm income by choosing the optimal production portfolio with regard to a set of constraints (e.g. resource availabilities). The implemented decision variables correspond to different farm activities, such as producing crops, purchasing machinery and hiring labor. Every agent in each simulation period (corresponding to one agricultural year) solves three MP-problems in MPMAS: investment, production and consumption. Such segmentation of decision making is required to reflect the allocation of resources and timing of farm activities. The full MP-optimization problem of one model agent consists of 2,027 decision variables (50 integers) and 1,569 constraints. MPMAS includes a statistically consistent agent population of 720 agents created according to the Monte-Carlo approach as described in Berger et al. (2006). Different assets (e.g. machinery, land) and capital endowments are assigned to each agent at the initialization of the simulation and updated over each period. The synthetic agent population represents 99% in terms of cultivated area and 74% in terms of number of all crop-producing farms at the five IMEA (Mato Grosso Institute of Agricultural Economics) survey sites (Brazilian Institute of Geography and Statistics 2006). A more detailed description of the parameterization and predictive performance of MPMAS at farm and municipality level is provided in the supplementary material.

4.2.3. Integrated yield gap assessment

Figure 4.1 illustrates how MONICA and MPMAS were conceptually combined and how different yield gap types were estimated. The highest yield level is Y_p, which is the yield of a crop cultivar when grown with water and nutrients non-limiting and biotic stress effectively controlled (Evans 1993b, 1993a; van Ittersum and Rabbinge 1997). The next lower level is the water-limited yield (Y_w), which is the most important benchmark for rain-fed crops. Y_a is both water- and nutrient-limited and is also affected by yield reducing factors, such as pests and diseases. Yield reducing factors were not considered in this study, since the availability of data on yield losses due to pests and diseases is limited. We further differentiate between a constrained and unconstrained Y_a level. At the unconstrained level, inputs, such as farm machinery and labor, are available at no costs, access to credit is unrestricted and technological innovations are available to all farm agents.

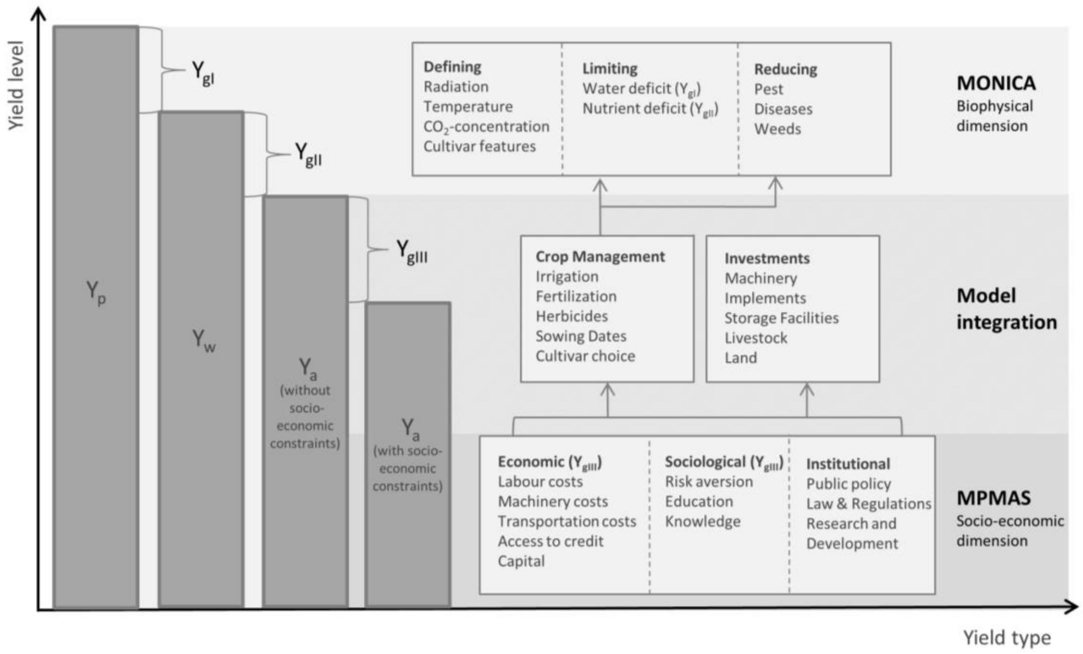


Figure 4.1 *Schematic representation of simulated yield levels, estimated yield gap types and conceptual integration of MONICA and MPMAS models.*

Three different types of yield gaps were estimated: 1) Y_{gI} due to water deficit, 2) Y_{gII} due to nitrogen deficit and 3) Y_{gIII} due to socio-economic constraints. Absolute Y_{gI} and Y_{gII} were calculated as the difference between Y_p, Y_w and Y_a following the GYGA protocol (Global Yield Gap Atlas 2016) with the difference that GYGA yield gap calculations are based on observed Y_a. The difference between Y_p and Y_a gives the total biophysical yield gap (Y_g). Relative Y_{gI} and Y_{gII} were calculated as described in Table 4.1. The relative share of Y_{gI} and Y_{gII} in the total biophysical yield gap was estimated as follows:

$$\mathrm{Y_{gI_{rel}}} = \frac{\mathrm{Y_{gI}}}{\mathrm{Y_g}} * 100;\ \mathrm{Y_{gII_{rel}}} = \frac{\mathrm{Y_{gII}}}{Yg} * 100$$

Y_{gIII} was calculated as the difference between all scenarios in which a socio-economic factor was set to an unconstrained level and all scenarios in which the same factor was set to the constrained (baseline) level (see section 4.4). Furthermore, the effect size of inter-annual and interregional climate variability, soil types, sowing dates, crop rotation, N fertilization on the total biophysical yield gap variance was estimated by conducting an analysis of variance (ANOVA) and subsequent calculation of eta squared values, which are an indicator for the magnitude of an effect (Levine and Hullett 2002). Table 4.1 summarizes the different yield levels, yield gap types, their definition and estimation/modelling approaches.

The integration of MONICA and MPMAS takes place at the crop management level: Socio-economic and institutional conditions are relevant for the agent decision-making process on long-term investments and crop management activities, which in turn have a direct influence on crop growth. Sowing dates, for instance, define the timing of the crop growth period and hence how much incoming light energy can be converted into biomass. Irrigation, fertilization and pesticide application determine how well yield limiting and yield reducing factors can be controlled and to which extent yield losses can be avoided. Technically, MONICA and MPMAS were linked through an online database. Simulated crop yields were stored in a MySQL server and accessed by MPMAS during the agent consumption stage, when the software updates expected crop yields with those simulated by MONICA.

Table 4.1 *Yield levels, yield gaps, their definition and modelling approach*

Abbr.	Yield level/ Yield gap	Definition	Model/Estimation
Y_p	Potential yield	Simulated potential yield without water and nutrient stress	MONICA
Y_w	Water-limited yield	Simulated yield without nutrient stress (rain-fed agriculture)	MONICA
Y_a	Actual yield	Simulated actual yield with water and nutrient stress	MONICA
Y_g	Biophysical yield gap	Difference between Y_p and Y_a	$\left(1-\frac{Y_a}{Y_p}\right)*100$
Y_{gI}	Yield gap due to water deficit	Difference between Y_p and Y_w	$\left(1-\frac{\mathrm{Y_w}}{\mathrm{Y_p}}\right)*100$
Y_{gII}	Yield gap due to nutrient deficit	Difference between Y_w and Y_a	$\left(1-\frac{Y_a}{Y_w}\right)*100$
Y_{gIII}	Socio-economic yield gap	Difference between unconstrained and baseline scenario	MPMAS

4.2.4. Yield gap assessment in double-cropping systems

In addition to yield gaps of individual crops, biophysical yield gaps were also calculated at the cropping system (CS) level, since soybean, maize and cotton are mainly produced in double-crop rotations in MT. In double-cropping systems, yields of individual crops are often lower than in single CSs, but the overall productivity and revenue tends to be higher due to the increased cropping intensity. Guilpart et al. (2017)proposed to estimate yield gaps at the CS level as the difference between the absolute yield potential (CSYp*) and the actual yield of any CS ($CSYa_i$). This approach has the advantage that yield gaps can be further disaggregated into the spatial/temporal arrangement and the management of individual crops. Guilpart et al. (2017) defines the CSYp* as the "combination of crops that gives the highest energy return per unit of land and time". Actual ($CSYa_i$) and potential ($CSYp_i$) yields of any CS were calculated as described in Table 4.2. The difference between CSYp* and CSYpi is the yield gap due to the spatial and/or temporal arrangement of crops ($CSYgA_i$), whereas the difference between $CSYp_i$ and $CSYa_i$ is the yield gap due to the management of individual crops within the current CS ($CSYgM_i$). We followed the approach proposed by Guilpart et al. (2017) to compare nine different soybean-maize CSs and six different soybean-cotton CSs (see section 4.3.1), with the difference that our calculations are based on dry matter yield instead of the energy return per unit of land and time. Table 4.2 gives an overview on the yield levels and yield gap types at the cropping system level and their definition and modelling/estimation approach.

Table 4.2 *Yield levels and yield gaps at the cropping system level, their definition and modelling approach based on Guilpart et al. (2017).*

Abbr.	Definition	Model/Estimation
CSYp*	Combination of crops that gives highest energy return per unit of land and time	MONICA;$\sup(\mathrm{CSYp}_i)$
$CSYp_i$	Potential yield at the cropping system level for *n* crops during a period of *m* years	MONICA;$\frac{1}{m}\sum_{j=1}^{n} Yp_{i,j}$
$CSYa_i$	Actual yield at the cropping system level for *n* crops during a period of *m* years	MONICA;$\frac{1}{m}\sum_{j=1}^{n} Yp_{i,j}$
$CSYg_i$	Total biophysical yield gap at the cropping system level	$\left(1-\frac{CSYa_i}{CSYp*}\right)*100$
$CSYgA_i$	Yield gap due to the spatial and/or temporal arrangement of individual crops	$\left(1-\frac{CSYp_i}{CSYp*}\right)*100$
$CSYgM_i$	Yield gap due to the management of individual crops	$\left(1-\frac{CSYa_i}{CSYp_i}\right)*100$

4.3. Experimental set-up

4.3.1. Crop modelling

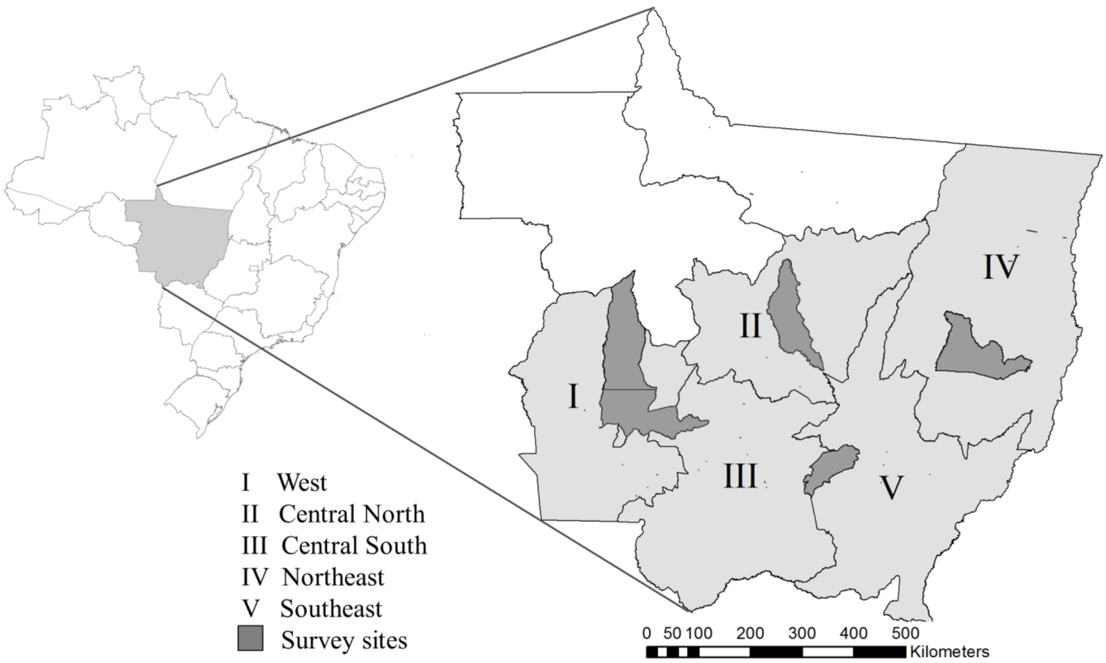


Figure 4.2 *Survey sites and corresponding macro-regions in Mato Grosso, Brazil.*

Survey sites and weather data. The yield gap analysis was carried out for five survey sites in MT, each of it being representative for one macro-region in MT (Instituto Mato-Grossense de Economia Agropecuária 2016a) (Figure 4.2). Taken together, the five survey sites provide the data basis for the yield gap analysis in this paper. The five survey sites and their respective macro-regions are: Canarana (Northeast), Campo Verde (Southeast), Sapezal (West), Sorriso (Central North) and Tangará da Serra (Central South). Weather data were gathered from meteorological stations located at the survey sites or – if not available – from stations nearby. The datasets comprise a 14-year period (1999 to 2013) and include daily measurements of the following variables: maximum and minimum air temperature, effective sunshine hours, precipitation, wind speed and relative air humidity (Instituto Nacional de Meteorologia 2015). Potential, water-limited and actual yields as well as corresponding yield gaps were simulated for each cropping season based on the daily weather data. Gaps in the datasets were filled with simulated data extracted from high resolution maps of dynamical climate projections for the Southern Amazon (Böhner et al. 2014). Figure 4.3 shows the average daily precipitation and temperature from 1999 to 2013 for weather stations at the five IMEA survey sites.

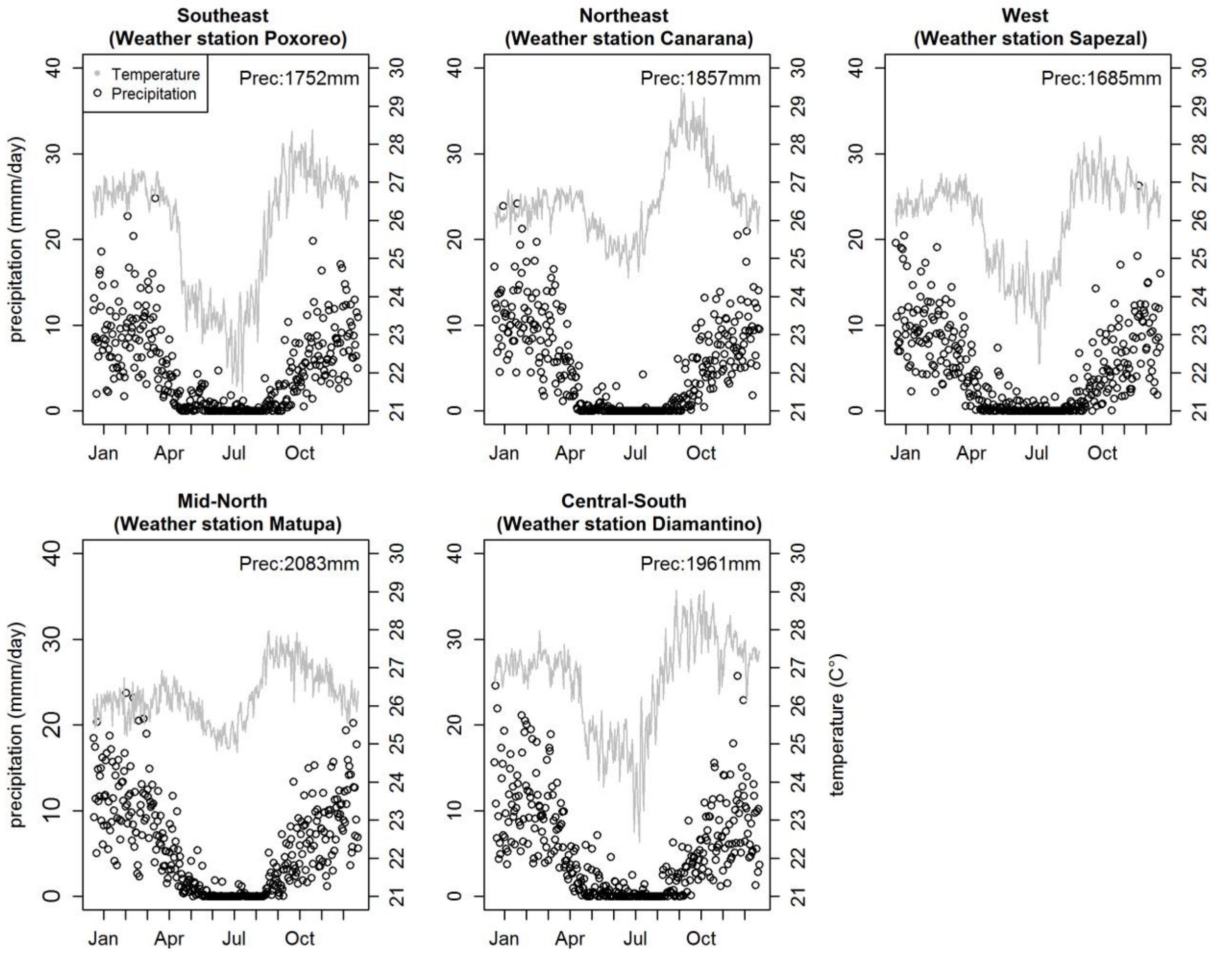


Figure 4.3 *Average daily precipitation (mm/day) and temperature (C°) and average annual precipitation between 1999 and 2013 at the weather stations Poxoreo, Canarana, Sapezal, Matupa and Diamantino, representative for the five studied macro-regions Southeast, Northeast, West, Mid-North and Central-South, respectively.*

Soil types. Soil types in each survey site were defined in accordance with soil maps published by the State Secretary of Planning (Secretaria de Estado de Planejamento e Coordenação Geral de Mato Grosso 2011). Based on these maps, six different soil classes were identified as well as the share of each soil class by survey site (Table 4.3). An input file was configured for each of these soil types, containing information on soil texture, organic carbon content, bulk and stone density for four different horizon layers (0-20cm, 20-50cm, 50-80cm, 80-200cm).

Table 4.3 *Survey sites, coordinates of weather stations, corresponding macro-regions, soil types and their share in total land by survey site in percentage*

Macro-region	Survey site	Geo-reference of weather station	Soil types	Estimated share of soil types (%)
Southeast	Campo Verde	Lat: −15.83, Long: −54.38 Alt: 450.00m	Ferralsol dys, Cambisol typ	90, 10
Northeast	Canarana	Lat: −13.47, Long: −52.27 Alt: 430.00m	Ferralsol dys, Plinthosol dys	60, 40
West	Sapezal	Lat: −13.54, Long: −58.81, Alt: 370.00m	Ferralsol dys	100
Mid-North	Sorriso	Lat: −10.25, Long: −54.91 Alt: 285.00m	Ferralsol dys	100
Central South	Tangará da Serra	Lat: −14.4, Long: −56.45 Alt: 286.30m	Acrisol dys, Arenosol dys, Ferralsol dys, Ferralsol typ	40, 40, 13, 7

Sowing dates and crop rotation. Crop yields were simulated within a crop rotation system composed by soybean in the first season and maize or cotton in the second season. Alternatively, cotton can be grown in rotation with a cover crop such as millet, where latter mainly serves to prevent soil erosion and enhance nitrogen cycling. Soybean is sown at the onset of the rainy season, while maize and cotton are sown between December and March (Instituto Mato-Grossense de Economia Agropecuária 2016a) (Figure 4.4). Soybean cultivars can be grouped into three maturity groups (MG): VII, VIII and IX. Midwestern Brazilian soybean cultivars of MG VII reach maturity in less than 115 days, MG VIII in 115 to 126 days and MG IX in more than 126 days (Alliprandini et al. 2009). In total, nine different soybean-maize, six soybean-cotton (consisting of different sowing dates and soybean MGs) and five millet-cotton cropping systems were implemented in MONICA to represent the most common cropping systems (CS) in MT (Table 4.4).

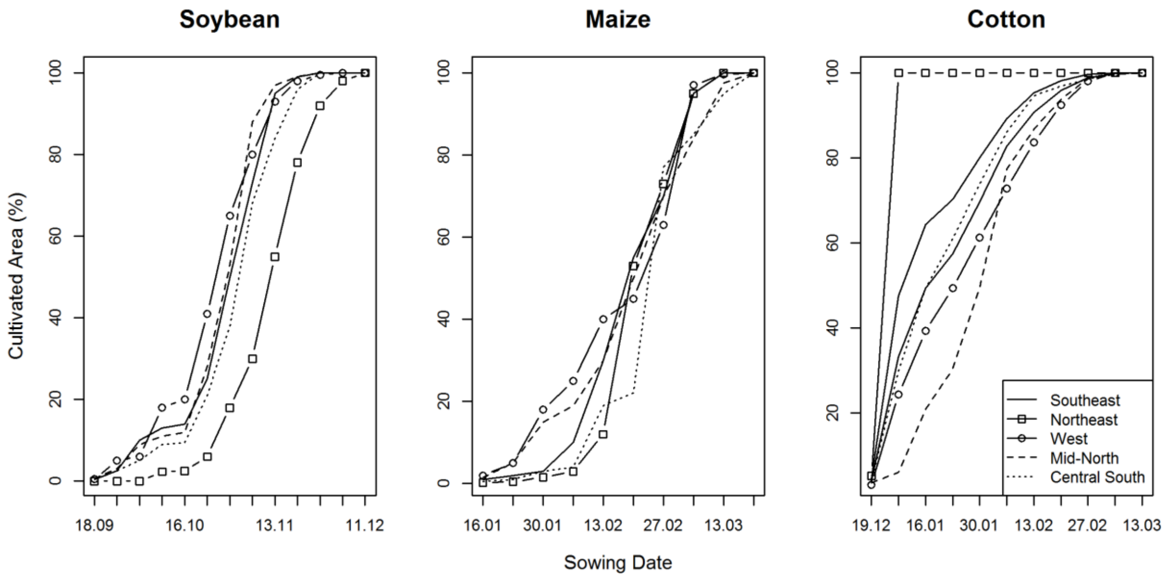


Figure 4.4 *Sowing period according to percentage of cultivated area for soybean, maize and cotton along the 2014/215 crop season in the five studied macro-regions of Mato Grosso, Brazil, based on (Instituto Mato-Grossense de Economia Agropecuária 2016a).*

Nitrogen fertilization. Maize and cotton yields were simulated in response to different N fertilization rates with ammonium sulfate as the source of nitrogen. In maize cultivation, nitrogen fertilization is applied in a single application a few days before sowing. Fertilization amounts and timing of application for cotton were determined in accordance with a database provided by Consultoria Focada na Análise do Agronegócio (2018). N fertilization rates for cotton were split into four parcels of 15%, 40%, 30% and 15% and applied at sowing and 25, 40 and 55 days after sowing. Soybean does not receive any N fertilization as it can satisfy large parts of its nitrogen demand by biological N_2 fixation (Salvagiotti et al. 2008). Table 4.4 summarizes the cropping systems, crop rotations, sowing dates and fertilization scheme implemented in the MONICA model.

Table 4.4 *Cropping systems, crop rotation, sowing dates and N fertilization rates used in the simulation experiment*

CS	1st season	Sowing dates	2nd season	Sowing dates	N fertilisation
1-4	Soy MG VII	1 Oct, 10 Oct, 20 Oct, 30 Oct	Maize	20 Jan, 6 Feb, 20 Feb, 6 Mar	0, 40, 80, 120, 160
5-7	Soy MG VIII	1 Oct, 10 Oct, 20 Oct		6 Feb, 20 Feb, 6 Mar	
8-9	Soy MG IX	1 Oct, 10 Oct		20 Feb, 6 Mar	
10-12	Soy MG VII	1 Oct, 10 Oct, 20 Oct	Cotton	15 Jan, 30 Jan, 15 Feb	0, 90, 140, 185, 230, 280, 450
13-14	Soy MG VIII	1 Oct, 10 Oct		30 Jan, 15 Feb	
15	Soy MG IX	1 Oct		15 Feb	
-	Millet	1 Oct		15 Dec, 30 Dec, 15 Jan, 30 Jan, 15 Feb	

4.4. Agent-based modelling

According to (Gil et al. 2016), four socio-economic factors are crucial in the decision-making process of farmers in MT: 1) machinery acquisition and maintenance costs, 2) labor costs, 3) access to rural credit and 4) access to technological innovations. One of the major recent technological innovations in MT was the release of short maturing soybean cultivars (MG VII). Following the approach of (Schreinemachers et al. 2007), for each of these socio-economic factors, two levels were defined in consultation with local experts: the first level represents the actual situation or baseline scenario, which assumes that current trends will persist and that no new external interventions are to be expected. In the unrestricted scenario, machinery acquisition and maintenance costs as well as labor costs were set to zero, credit limits of the subsidized governmental credit programs were removed, and soybean cultivars of MG VII were assumed to be available to all agents as of the first simulation period. These factors and their respective levels were combined in a full factorial design (2^4), resulting in a total number of 16 scenarios (Table 4.5). The main effect of each factor on crop yields was calculated as the difference between all scenarios in which the factor was set to the unconstrained level and all scenarios in which the same factor was set to the baseline level. The simulation results were also compared in terms of land-use and farm revenue change. Additional information on MPMAS model agents and the socio-economic factors can be found in the supplementary material.

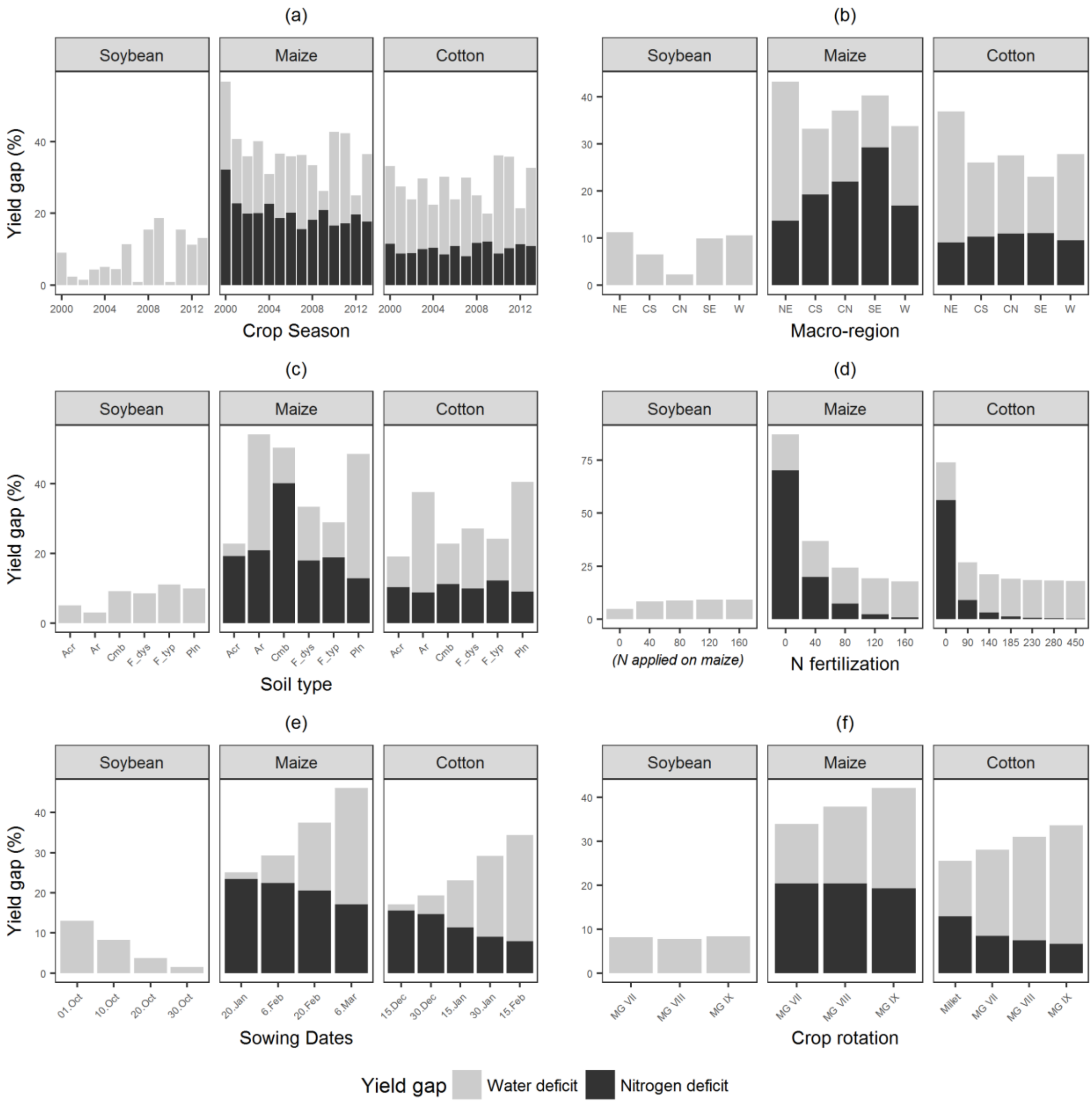
Table 4.5 *Full factorial design as implemented in MPMAS, where "−" reflects the baseline scenario and "+" the unrestricted scenario.*

Factor/ level	Machinery	Labour	Credit supply	Technological innovation
1	−	−	−	−
2	+	−	−	−
3	−	+	−	−
4	−	−	+	−
5	−	−	−	+
6	+	+	−	−
7	+	−	+	−
8	+	−	−	+
9	−	+	+	−
10	−	+	−	+
11	−	−	+	+
12	+	+	+	−
13	+	+	−	+
14	+	−	+	+
15	−	+	+	+
16	+	+	+	+

4.5. Results

4.5.1. Biophysical yield gaps

Simulated soybean, maize and cotton Y_g due to water and nutrient deficit accounted for 0.3 t ha^{-1} (8%), 2.3t ha^{-1} (37%) and 0.55 t ha^{-1} (28%), respectively. Lowest yield gaps were simulated for soybean, as it is planted at the onset of the rainy season and can satisfy large parts of its nitrogen requirement through biological N fixation. Water deficit was responsible for 46% and 64% of simulated maize and cotton yield gaps (Y_{gI}), respectively, whereas the remaining part of the yield gap was attributable to insufficient nitrogen supply (Y_{gII}). In the simulations, cotton was less limited by nitrogen deficit, as model agents (and real-world famers) tend to apply large amounts of N fertilizer and split them into several applications, thereby decreasing the risk of N leaching. Figure 4.5 shows the simulated soybean, maize and cotton yield gaps according to different cropping seasons, macro-regions, soil types, N fertilization rates, sowing dates and crop rotations schemes.



Note: Regions: NE-Northeast, CS–Central South, CN-Central North, SE-Southeast, W-West; Soils: Acr-Acrisol, Ar-Arenosol, Cmb–Cambisol, F_dys-Ferralsol dys, F_typ-Ferralsol typ, Pln-Plinthosol.

Figure 4.5 *Simulated soybean, maize and cotton yield gaps (%) according to a) different crop seasons (1999-2013), b) macro-regions, c) soil types, d) N fertilization rates, e) sowing dates and f) crop rotation schemes in Mato Grosso, Brazil.*

Inter-annual climate variability. Inter-annual climate variability demands a high level of flexibility and careful crop management from farmers in MT, particularly from those who practice double-cropping in a rain-fed system. When planted too early in the season, irregular rainfalls cause severe soybean yield losses; in dry years a complete replanting may be necessary. The highest soybean Y_{gI} was simulated for the crop season 2008/2009, which was one of the seasons with the lowest rainfall amount. Our simulations suggested that a combination of relatively high temperatures and low rainfalls led to above-average maize and cotton Y_{gI} in the subsequent seasons 2010 and 2011. Heavy rainfalls increase the risk of N leaching, which is particularly an issue in maize cultivation where N is applied all at once at sowing. Simulated maize Y_{gII} were most pronounced in 2001 (31%), whereas cotton Y_{gII} were almost stable throughout the years (≈10%).

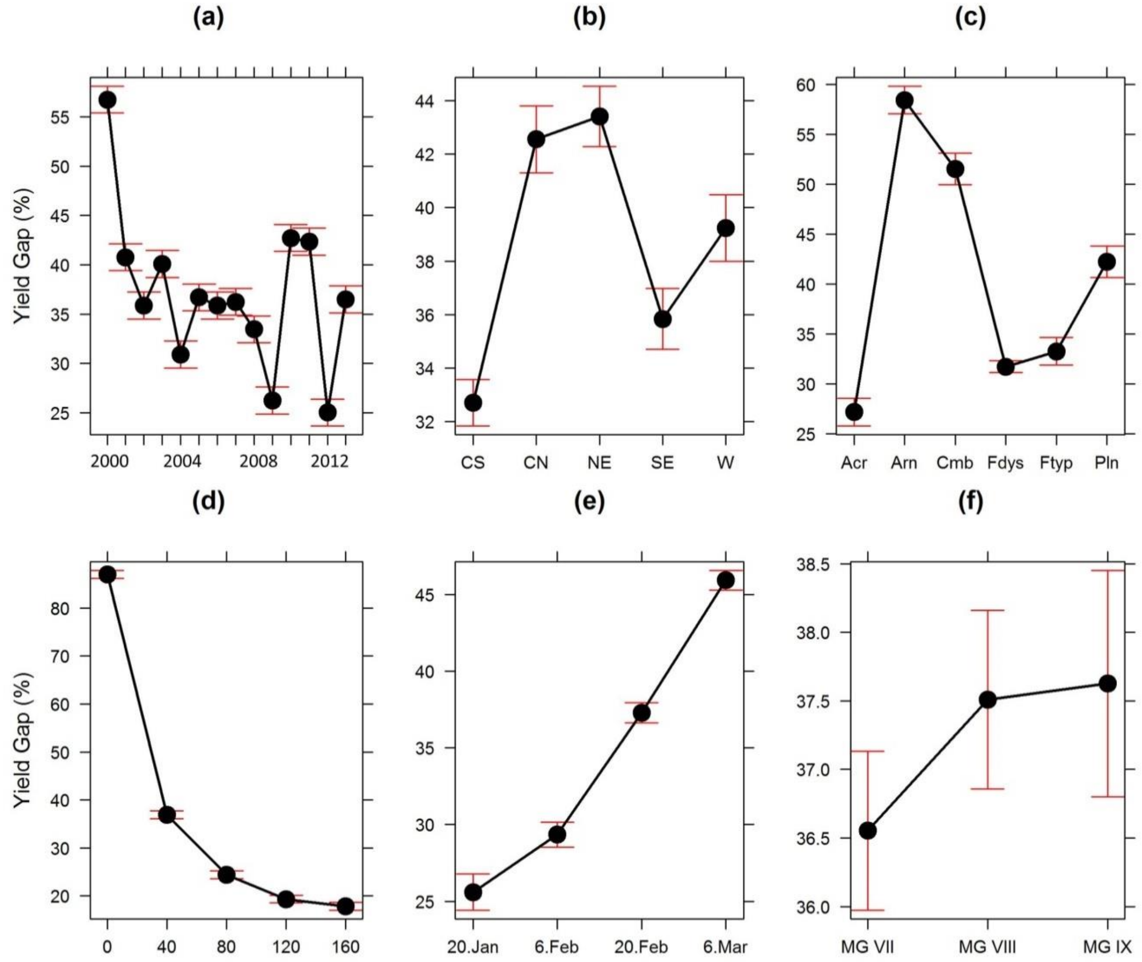
Inter-regional climate variability. Temperature and rainfall patterns vary between both crop seasons and macro-regions, determining the time window for sowing and harvesting of crops (see section 4.3.1). High values for soybean Y_{gI} were simulated for the Northeast (11%), West (10%) and Southeast (10%), which are the macro-regions with the lowest precipitation during the soybean growing period. Simulated maize and cotton Y_{gI} were highest in the Northeast (29%) and lowest in the Southeast (12%), which was due to soil properties and high (low, respectively) temperatures during the dry season and corresponding crop evapotranspiration. The simulated N deficit on maize was most pronounced in the Southeast (29%), whereas cotton Y_{gII} did not present much variation across macro-regions.

Soil types. According to our simulations, inter-regional yield gap variability was not exclusively a result of different climate conditions, but was also related to different soil types, since these two factors interact, defining the soil water availability and logging (see section 4.3.1). Simulated soybean Y_{gI} was most evident on typic ferrosols (11%) and cambisols (9%). Highest maize and cotton Y_{gI} were simulated on plinthosols (34%), which have low water permeability and are susceptible to water logging as well as on arenosols (31%), a sandy-textured soil type with low water holding capacity. Simulated maize Y_{gII} amounted to 40% on cambisols, whereas Y_{gII} differences among other soil types and in cotton production were rather small.

N fertilization. Without N fertilization, simulated maize and cotton Y_{gII} accounted for 70% and 56%, respectively. An application of 40 kg N ha^{-1} reduced simulated maize Y_{gII} to 20%. Additional N applications further minimized Y_{gII} but simulated actual yield gains were rather small (< 350 kg ha^{-1}). Simulated cotton Y_{gII} dropped to less than 10% of Y_p with an application of 90 kg N ha^{-1}. Fertilization rates larger than 185 kg N ha^{-1}, however, had little impact on simulated cotton yields. Our simulations indicated that soybean Y_{gI} slightly increased when maize and cotton were fully supplied with N, since the water uptake of a well-nourished and fully growing plant increases, thus reducing the water availability for subsequent crops.

Sowing dates and crop rotation schemes. Simulated yield gaps were also related to sowing dates and crop rotation schemes. Soybean Y_{gI} accounted for 13% when planted at the 1st of October but decreased constantly with every ten days of sowing delay. Despite this clear advantage of postponing soybean production, trade-offs with maize and cotton production need to be considered: the later second-season crops are sown, the higher the simulated Y_{gI} and the risk of a complete crop failure due to water deficit. Simulated maize and cotton Y_{gI} increased to more than 20% when planted after the 15th of February. On the other hand, simulated maize and cotton Y_{gII} decreased by 19% and 47%, respectively, when planted at the latest sowing date, suggesting that less nitrogen was lost through leaching. A similar pattern was simulated for crop rotation schemes: when preceded by late maturing soybean cultivars (MG VIII, MG IX), simulated maize and cotton Y_{gI} tended to be higher, whereas Y_{gII} decreased. Different soybean MGs, instead, were nearly equally affected by water deficit in the simulations.

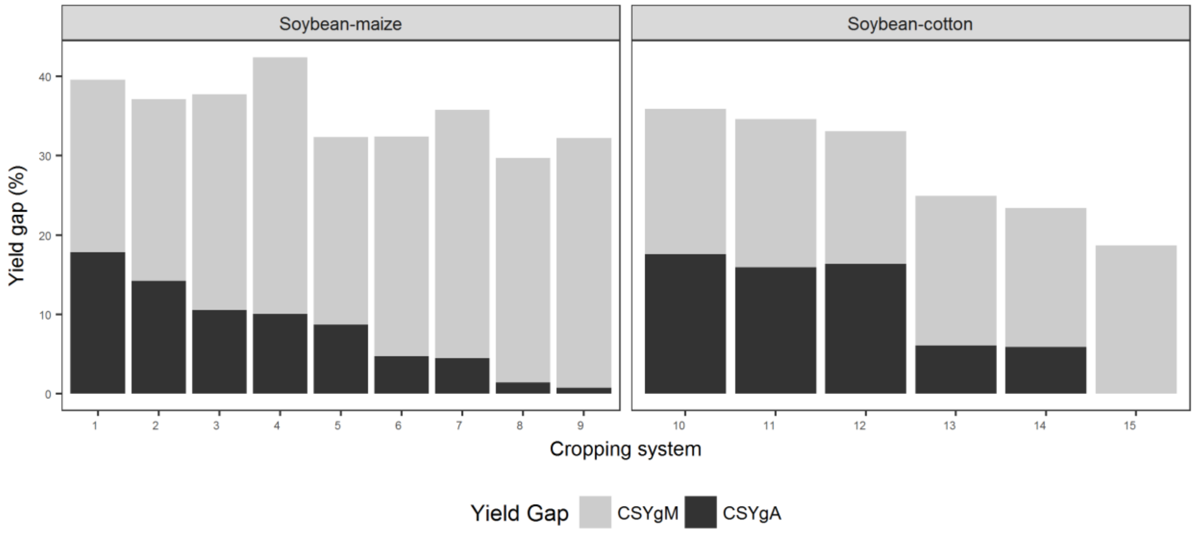
Main effect sizes of explaining factors. The ANOVA and subsequent calculation of effect sizes (eta-squared values) suggests that simulated total soybean Y_g variance can be explained to 18% by inter-annual climate variability, 10% by sowing dates, 4% by inter-regional climate variability, 2% by soil types and 1% by different fertilization rates (R^2 = 0.36). Different N fertilization rates explained 61% of the simulated maize Yg variance, whereas soil types, different crop seasons, sowing dates, inter-regional climate variability and crop rotations were responsible for 8%, 5%, 4%, 2% and 1% of maize Y_g variance, respectively (R^2 = 0.81). Simulated cotton Y_g variance was mostly due to N fertilization (65%), followed by sowing dates (5%), crop seasons (5%), inter-regional climate variability (4%), soil types (4%) and crop rotations (1%, R^2 = 0.84). Detailed ANOVA results can be found in the supplementary material. Figure 4.6 shows the simulated effect sizes of the explaining factors on maize Y_g variance.



Note: Regions: CS–Central South, CN-Central North, NE-Northeast, SE-Southeast, W-West; Soils: Acr-Acrisol, Ar-Arenosol, Cmb–Cambisol, Fdys-Ferralsol dys, Ftyp-Ferralsol typ, Pln-Plinthosol.

Figure 4.6 *Simulated effect sizes according to different (a) crop seasons, (b) macro-regions, (c) soil types, (d) fertilization rates, (e) sowing dates and (f) soybean maturity groups on maize yield gap variance in Mato Grosso, Brazil.*

Yield gaps in double-cropping systems. Simulated CSYg in soybean-maize rotations amounted to 33%, whereas simulated CSYg in soybean-cotton rotations was about 27% (Figure 4.7). The lowest CSYg in soybean-maize rotation was simulated for CS 8, composed by soybean MG IX planted on the 1st of October and maize planted on the 20th of February. The lowest soybean-cotton CSYg was simulated for CS 15 composed by soybean MG IX planted on the 1st of October and cotton planted on the 15th of February. It was the combination of cultivars and sowing dates, which gave the highest potential dry matter yield return per unit of land and time (CSY_p*) and where the yield gap due to the temporal arrangement of crops (CSYgA) was equal to zero. In our simulations, rotations composed by late maturing soybean varieties (MG VIII and MG IX) and maize or cotton planted on late sowing dates gave the lowest CSYgA. However, the more the cultivation of second season crops was postponed the higher the yield gaps due to the management of individual crops (CSYgM).



Note: Cropping Systems are defined as: 1: MG VII/ 20jan, 2: MG VII/ 6Feb, 3:MG VII/ 20Feb, 4:MG VII/ 6Mar, 5: MG VIII/ 06Feb, 6: MG VIII/ 20Feb, 7: MG VIII/ 6Mar, 8: MG IX/ 20Feb, 9:MG IX/ 6Mar, 10: MG VII/ 15Jan, 11: MG VII/ 30Jan, 12: MG VII/ 15Feb, 13:MG VIII/ 30Jan, 14: MG VIII/15Feb, 15: MG IX/15Feb.

Figure 4.7 *Simulated yield gaps for 15 alternative soybean-maize and soybean-cotton cropping systems in Mato Grosso, Brazil.*

4.5.2. Socio-economic yield gaps and constraints

The MPMAS simulations revealed in most cases rather small yield increasing effects of unconstrained access to machinery, labor, credit and technological innovation. On average, model agents increased their soybean, maize and cotton yields by 1% (0.05 t ha^{-1}), 2.3% (0.31 t ha^{-1}) and 15% (0.3 t ha^{-1}; Figure 4.8), respectively. However, there were large differences between constraints and farm size categories, including scenarios in which agent crop yields even decreased, as described in the following sections.

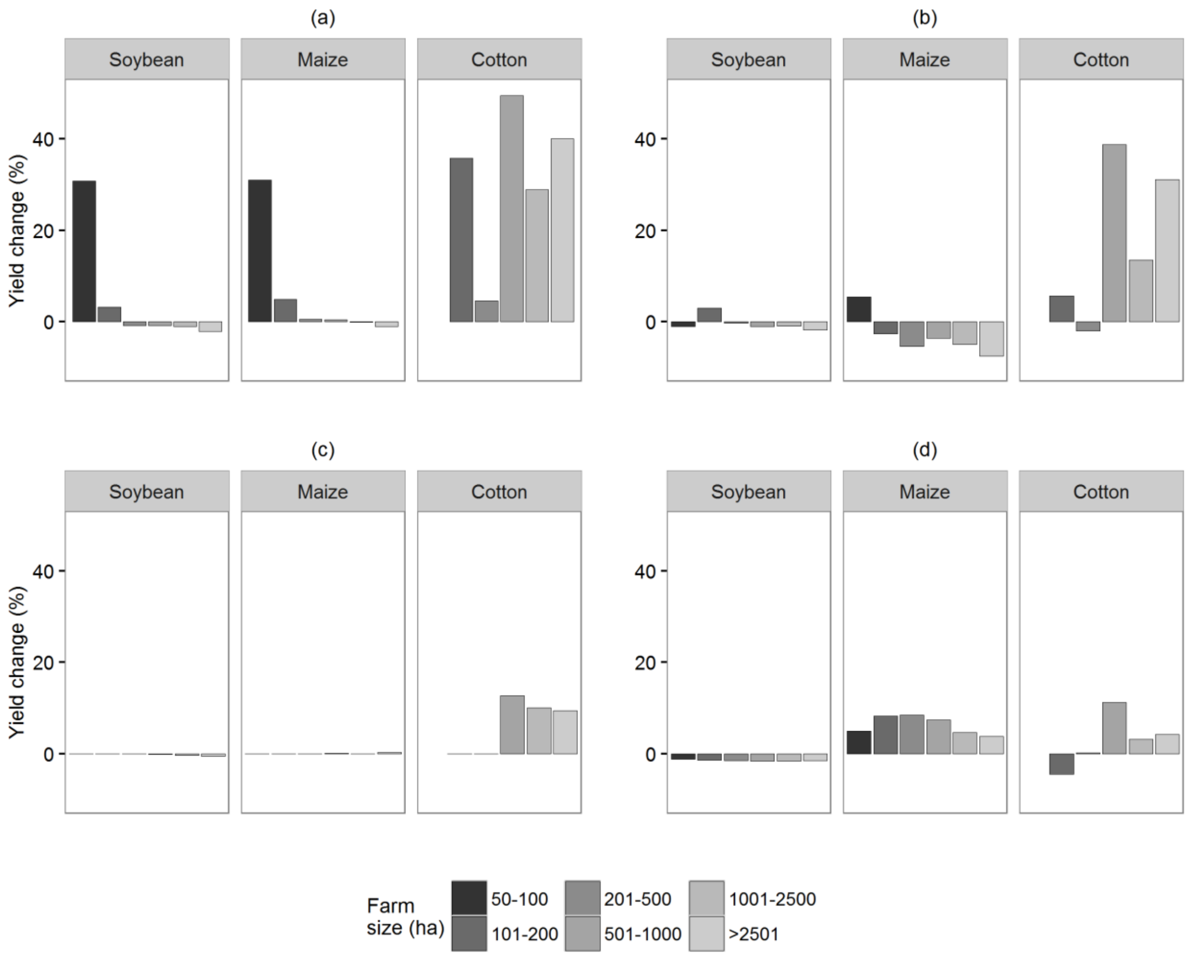


Figure 4.8 *Simulated soybean, maize and cotton yield changes due to an unconstrained access to a) machinery, b) labor, c) credit and d) technological innovation among model agents of different farm sizes in Mato Grosso, Brazil.*

Machinery constraints. Simulation results suggested that soybean, maize and cotton yields could increase by 4% (0.13 t ha^{-1}), 5% (0.3 t ha^{-1}) and 23% (0.19 t ha^{-1}), respectively, if machinery was not a limiting production factor. In the unrestricted scenario, maize and soybean yields among agents with less than 100 ha were simulated to increase by 28% (1.65 t ha^{-1} and 0.9 t ha^{-1}, respectively). Model agents of this farm size category did not produce cotton due to the high investment requirement and production costs that only pay-off at a certain scale. On large-scale agent farms (> 500 ha), an unconstrained access to machinery was simulated to lead to a shift from soybean-maize production to the more machinery intensive soybean-cotton rotation. The highest cotton yield improvements were simulated for agents with 501−1,000 ha (44%, 0.3 t ha^{-1}) and agents with more than 2,500 ha (31%, 0.25 t ha^{-1}).

Labor constraints. In the unrestricted scenario, simulated average soybean and maize yields decreased by 1.4% (0.04 t ha^{-1}) and 6% (0.16 t ha^{-1}), whereas simulated cotton yields increased by 13.7% (0.08 t ha^{-1}). Simulation results suggested that an unconstrained access to labor resulted in an increasing number of workers and drivers hired with permanent contracts (72.5%) and a clear cutback of workers and drivers hired with temporary contracts (− 93.5%). Consequently, large-scale farm agents shifted their production from soybean-maize to soybean-cotton rotation and increased the share of cotton planted on early sowing dates (15.12, 15.01). The highest cotton yield increases (35% or 0.2 t ha^{-1}) were simulated for large-scale model agents (501-1,000 ha, > 2,500 ha).

Credit constraints. In our simulations, an unconstrained access of agents to subsidized credit lines led to a shift from late to early maturing soybean cultivars and an increased share of capital-intensive crop rotation schemes. In the unrestricted scenario, simulated average cotton yields increased by 6% (0.03 t ha^{-1}), whereas simulated soybean and maize yields remained nearly unchanged. An unlimited access to subsidized credit did not have any impact on simulated crop yields among small-scale model agents, suggesting that current credit limits (R$1 million) were sufficient to satisfy the demand of farms with less than 1,000 ha.

Technological innovation. In the unrestricted scenario, all farm agents were granted immediate access to soybean cultivars of MG VII. In the first four years of simulation, the average area cultivated with soybean MG VII was therefore twice as high as in the baseline scenario (938 ha compared to 402 ha). Since early maturing soybean cultivars have lower yields than late maturing cultivars, a timely adoption of soybean MG VII was simulated to result in an average soybean yield decrease of 2% (0.04t ha^{-1}). On the other hand, simulated maize and cotton yields increased by 6% and 3%, respectively, as model agents were able to shift their cultivation to early sowing dates.

Land use and revenue change. The simulation results suggested that an unrestricted access to machinery, labor, credit and technological innovation would lead to an average cropland expansion of 22% (Figure 4.9a). Furthermore, a shift from soybean-maize to soybean-cotton rotation was simulated for large-scale agents (> 500 ha). An unconstrained access to machinery and labor led to an increase of simulated farm revenue by 11% and 14%, whereas an unlimited access to credit and innovation mainly benefitted medium and large-scale farm agents. Simulated farm revenues increased, on average, by 7% in the unrestricted scenario (Figure 4.9b). Production costs and selling prices in MPMAS were kept constant over years to isolate direct simulated effects of socio-economic factors. Therefore, simulated changes in revenue were strictly influenced by changes in crop yields and/or land use.

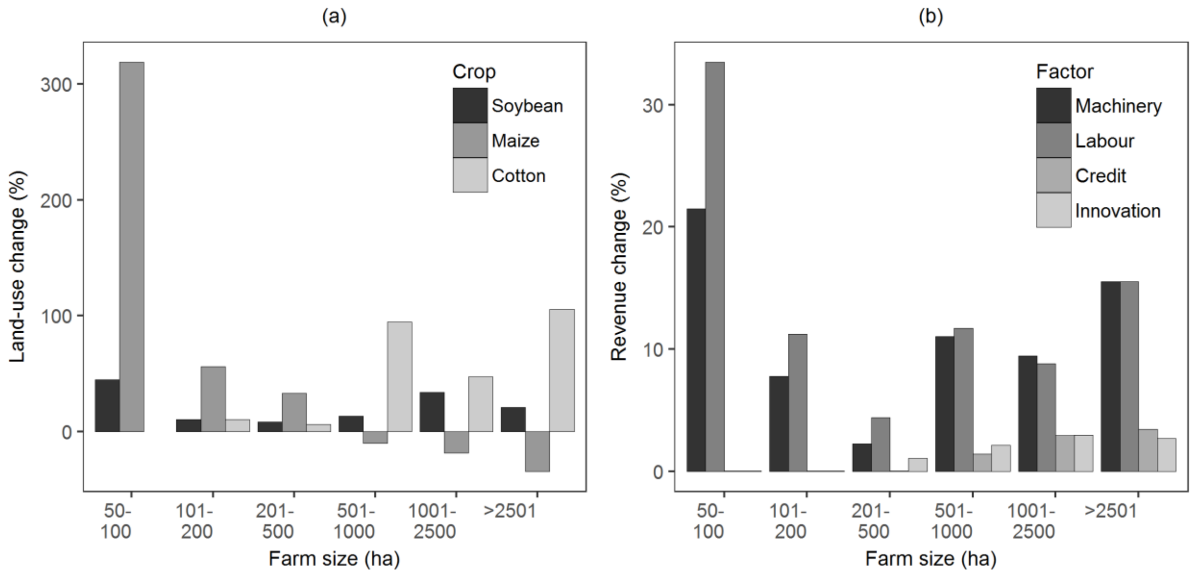


Figure 4.9 *Simulated (a) land-use change for soybean, maize and cotton and (b) revenue change according to farm size categories between the baseline and unrestricted scenario in Mato Grosso, Brazil.*

4.6. Discussion

This study followed a bio-economic simulation approach to decompose yield gaps in the Southern Amazon into their biophysical and socio-economic dimensions. The simulation results suggested that yield gaps can be reduced through improved water and nutrient management, appropriate cultivar–sowing date combinations as well as a removal of socio-economic constraints. The potential and limitations of each of these solutions will be discussed in the following.

Irrigation. Closing biophysical yield gaps through improved water and nutrient management, as proposed by Mueller et al. (2012), has a high potential of increasing yield per hectare production. Simulation results suggested that a shift from rain-fed to irrigated agriculture could minimize soybean, maize and cotton yield gaps in MT by 8% (0.3 t ha^{-1}), 17% (1.06 t ha^{-1}) and 18% (0.9 t ha^{-1}). Our findings are comparable to those of other studies: Sentelhas et al. (2015) reported average soybean yield gaps to water deficit of 18% (0.8 t ha^{-1}) for two locations in MT, while Global Yield Gap Atlas (2016) found drought-related maize yield gaps of 18% (1.7 t ha^{-1}). At present, agriculture in MT is mainly rain-fed. A change to (partially) irrigated agriculture has two major limitations: 1) installing irrigation systems is costly and likely not profitable for many farmers, 2) irrigation stands in conflict with limited water resources. At a global scale, freshwater resources for irrigation would have to increase at least by 146% for yield gap closure, exceeding sustainable levels of freshwater consumption in several countries (Davis et al. 2017). In MT, additional water resources of 15-28 km^3 yr^{-1} would be needed to satisfy the irrigation demand of all cropland (Lathuillière et al. 2016).

Nutrient management. Nutrient management plays a crucial role in yield gap closure (Mueller et al. 2012) and was identified as one of the most important yield gap explaining factors in yield gap studies worldwide (Beza et al. 2016). Our simulation results indicated that maize and cotton yield gaps could be reduced by 20% (1.2 t ha^{-1}) and 10% (0.5 t ha^{-1}), respectively, if N supply was not a limiting production factor. On the other hand, we found that N fertilization rates greater than 80 kg N ha^{-1} and 185 kg N ha^{-1} had rather small yield increasing effects on simulated maize and cotton crop yields, respectively. Furthermore, the simulation results pointed at cotton being less affected by nitrogen deficiency than maize, which might be due to the higher N rates applied to cotton in the simulation experiment as well as to the splitting and gradual application of N (see section 4.3.1). Since an excessive use of synthetic N is one of the principal sources of N leaching to groundwater and ammonium losses to surface water (Norse and Ju 2015), N management strategies that enhance the efficiency of nitrogen utilization, such as an improved timing of application or appropriate crop rotations and tillage systems (Fageria and Baligar 2005), might serve as an sustainable alternative for yield gap closure.

Sowing Dates. A precise timing of cropping activities as well as a thoughtful choice of cultivars is one of the most important management practice for yield gap closure (Beza et al. 2016). We found that soybean, maize and cotton yield gaps could be reduced to less than 2%, 25% and 17% of Y_p, respectively, if the most appropriate sowing dates were chosen. Optimal cultivar‒sowing date combinations for several crops and soil types and for each municipality were defined by the Brazilian Ministry of Agriculture, Livestock and Food Supply (MAPA) in order to reduce the risk of crop failure to climatic adversities (Ministério da Agricultura, Pecuária e Abastecimento 2017). However, MPMAS simulations revealed that adhering to these sowing date–cultivar combinations may not always be possible: farm machinery and labor constraints, limited access to credit and technological innovation may lead to suboptimal plantings and hence high yield gaps.

Double-cropping systems. Growing two or even three crops in one season has become a popular alternative to single-cropping systems: between 2001 and 2009, the area under double cropping in MT increased from 0.5 to 2.9 million hectares (Spera et al. 2014). In multiple-cropping systems, trade-off effects among several crops must be considered when searching for suitable combinations of crops with higher yields and finally economic returns. In the case of MT, we found that low yield gaps at the CS level were obtained when late maturing soybean cultivars (MG VIII and MG IX) were combined with maize and cotton planted at late sowing dates, even though yield gaps due to the management of individual crops were quite high in these crop rotations. In a case study on four locations in Bangladesh, Guilpart et al. (2017) demonstrated that improving the spatial arrangement of crops can give higher productivity gains than improving the management of individual crops. Our findings suggested that an improvement of the overall farm productivity may be achieved without closing yield gaps of individual crops and that high yield gaps were not per se an indicator of poor farm performance.

Land-use change. Recent soybean production increases observed in MT were mainly due to an expansion of crop land rather than due to an increase in productivity (Brazilian National Supply Company 2016b). Most of this expansion took place on previously cleared pasture, resulting in a temporal decoupling of deforestation and soy production in the late 2000s (Cohn et al. 2016a). Our simulation results suggested that a removal of socio-economic constraints may advance the expansion of cropland (22%) rather than an increase in crop yields (6.1%). Moreover, large-scale farmers might shift their production systems from soybean–maize to soybean–cotton or millet–cotton rotations. These model-based findings indicated that incentives for yield gap closure (e.g. improved access to subsidized credit) in MT, might result in unintended side effects, such as the replacement of food crops by cash crops or an expansion of cropland. Particularly in Brazil, where a revised version of the Forest Code more than halved the area to be reforested (Soares-Filho et al. 2014), there is a high risk that abundant land resources undermine efforts for closing yield gaps through sustainable intensification. Environmental regulations preventing further deforestation as well as political and economic incentives for sustainable intensification could help to reverse this trend.

Data availability limitations. Our findings are based on simulation experiments, which are subject to data availability and data quality constraints: One limitation at the crop modelling stage was that no robust data was available to calibrate the MONICA model to specific Y_p and Y_w levels. Instead, the model had to be calibrated to actual farmer yields, which are often limited by biotic stresses (e.g. animal pests, pathogens, weeds). Consequently, Y_p, and Y_w and resulting Y_g are quite low when compared to other studies, as they only account for abiotic (water- and nutrient deficit) stresses. Nonetheless, the comparison of simulated and observed crop yields indicated that the performance of MONICA to simulate crop growth under sub-tropical climatic and edaphic conditions is within acceptable limits. Incorporating more detailed nutrient dynamics of acid tropical soils into the model could help to further increase MONICA´s robustness in the study area, since acid soils' nitrate and ammonia transport and turn-over can be different to temperate soils. In addition, field surveys on risk aversion and other behavioral factors could help to gain a more complete picture of farmer´s decision making process in MT.

4.7. Conclusion

The overall objective of this study was to decompose yield gaps in the Southern Amazon into their biophysical and socio-economic dimensions. Although yield gaps in MT appear relatively small when compared to other world regions (Licker et al. 2010; Mueller et al. 2012), the simulation experiments revealed that average biophysical yield gaps in the Southern Amazon may account for one quarter of potential yields. A removal of the most pressing socio-economic constraints was simulated to have a slight yield-increasing effect with unintended side effects, such as an expansion of croplands and a shift from food to cash crops. Improved water and nutrient management, appropriate cultivar–sowing date combinations as well as an unrestricted access to machinery and labor were identified as key measures of yield gap closure. However, each solution comes with its own limitation either in form of increased pressure on limited environmental resources or incompatibility with individual farmer objectives. In double-cropping systems, as prevalent in MT, high yield gaps of individual crops are not necessarily an indicator of inefficiency but may instead lead to increased overall farm productivity. Furthermore, abundant land resources have given only limited economic incentives for yield gap closure in the past: between 2001 and 2010, soybean production increases in MT were mainly due to cropland expansion either into intact forests or previously cleared pasture areas (Macedo et al. 2012). In the coming decades, however, yield gap closure might gain increasing importance among farmers in MT, as potentially available land for further legal expansion of cropland production in MT is becoming scarce (Morton et al. 2016). The coupling of a crop growth and an agent-based simulation model allowed us to gain a much deeper insight into the potentials and limitations of yield gap closure in the Southern Amazon than disciplinary model approaches could do. We therefore conclude that considering both biophysical and socio-economic factors in an integrated yield gap assessment helps to draw a more complete picture of sustainable measures for yield gap closure.

Chapter 5. How to increase farm income and land use intensification on highly mechanized double cropping systems? The case of sunflower in Mato Grosso, Brazil

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A previous version of this chapter has been published[7] in the Proceedings of the 5th Baden-Württemberg High Performance Computing Symposium.

Abstract

Brazil is among the world's largest agricultural producers. The Brazilian state of Mato Grosso (MT), located at the dynamic agricultural frontier in the Cerrado-Amazon transition zone, is the country's most important grain, fiber, and meat producer. This study assesses the diffusion of sunflower cultivation in MT, where highly dynamic double-crop systems are employed by large-scale commercial farms. The diffusion of sunflower was assessed by an integrated modeling approach that combines an agent-based model with an agro-ecosystem model and simulates farm-level decision-making under the consideration of resource availability and agroecological constraints. Simulation results indicate that adopting sunflower cultivation increased farm income and had a positive impact on land-use intensification. The study presents the first estimate of potential sunflower production in MT and, then, investigated barriers to its adoption and its economic impact at farm and regional levels.

5.1. Introduction

A major challenge that our society currently faces is to ensure a sustainable supply of food in the case of dwindling natural resources and rising global population and wealth. Also, as

[7] Carauta, M., Sousa, L., Hampf, A., Troost, C., Libera, A., Berger, T., 2018. Simulating the impact of innovation diffusion in agriculture using agent-based modeling and High-Performance Computing. Proceedings of the fifth Baden-Württemberg High Performance Computing Symposium (5th bwHPC-Symposium). Freiburg, Germany.

economic growth and continuing urbanization increases the consumption of meat, top agricultural producing countries have a significant role in addressing such challenges. In this context, Brazil is one of the most significant players in global food production; consequently, what happens at its agricultural frontier (e.g., the federal state of Mato Grosso - MT) has a direct impact worldwide. MT is Brazil's largest agricultural producer and has its economy mainly characterized by large-scale commercial agriculture, consisting of widespread and highly mechanized double-cropping systems.

One main comparative advantage in MT is the well-established rainy season which allows farmers to cultivate two crops in the same cropping season and on the same area. On the one hand, double-cropping systems in MT contribute to increased farm income as well as better use of production resources while reducing exposure to market and climatic risks. On the other hand, it can increase the incidence of pest and diseases due to (1) intensification of land use; (2) the use of same crop rotation every year or; (3) the lack of a prolonged winter or fallow season (to break the development of pest and diseases) (Dias et al. 2016; Antonio et al. 2012; Matsuura et al. 2017; Carvalho et al. 2017). In addition, since sunflower have a shorter growing cycle than maize and cotton, sunflower can be an alternative crop for second season in MT since maize and cotton usually suffer from water deficit when cultivated after soybean.

Against this background, the introduction of sunflower emerges as a way of improving the agricultural production systems in MT. Recent evidence suggests that sunflower cultivation in succession to soybean as a second crop can: (1) reduce environmental impacts due to better use of resources and land intensification, (2) generate new sources of income with small amounts of additional investment, (3) enhance crop diversification, (4) reduce risk with water stress due to its drought tolerance, (5) improve nutrient cycling, and (6) reduce nematode population (Dias et al. 2016; Matsuura et al. 2017; Castro and Leite 2018; Tarsitano et al. 2016).

Despite the potential benefits of sunflower, little is known about its impact on farm income and land-use intensification. To our knowledge, there is no previous study that has comprehensively investigated how sunflower yields respond to socio-economic and environmental conditions in MT. Also, there are no simulated results regarding potential sunflower production. In addition, land use for sunflower production in MT accounts for approximately 55,000 hectares on average over the last ten years – which is approximately 2% of maize land use (Brazilian National Supply Company 2018). Recent evidence suggests that sunflower adoption is constrained by: (1) limited market structure (e.g., there are only two sunflower-processing facilities), (2) technological limitations regarding plant breeding and pest management, and (3) low level of cropping knowledge in comparison with well-established crops, like soybean and maize (Sousa et al. 2018).

This study advances the modeling approach of Carauta et al. (2017a) and Hampf et al. (2018) and seeks to investigate the impact of innovative agricultural practice (sunflower) on farm income and highly mechanized double-crop systems. The objective of this study is to (1) simulate the sunflower production potential in MT, (2) simulate the diffusion path of sunflower adoption in MT and identify barriers to its adoption and, (3) evaluate the economic impact of sunflower adoption at farm level. To achieve these objectives, we applied an integrated assessment (IA) approach, which combines an agent-based model (ABM) with a crop growth model. This approach takes into consideration a heterogeneous farming population, economic incentives, and socio-economic/environmental constraints.

5.2. Materials and methods

5.2.1. Study region

The federal state of MT is the third largest state by area in Brazil. It is home to a unique share of wildlife habitats with three different ecosystems (Cerrado – savannah vegetation, Amazon rainforest, and Pantanal – wetlands) and currently leads the national production of soybean, maize, cotton, sunflower, and beef cattle (Brazilian National Supply Company 2018). Agricultural systems in MT mainly consist of large-scale agriculture with highly mechanized double cropping systems. Mato Grosso's main comparative advantage is its climate and topography. The well-defined rainy season allows farmers to grow two crops per cropping season while its flat land permits the extensive use of machineries. The first season begins in September/October with the onset of the rainy season, whereas the second one starts in January/February. The main double cropping systems observed in MT are soybean-maize, soybean-cotton, and cover crop-cotton. Another recent crop rotation scheme is the cultivation of sunflower after soybean, which was established in the mid-2000s in the municipality of Campo Novo do Parecis and its surroundings (western region of MT).

5.2.2. Integrated modeling approach

Our IA approach simulates farm-level decision-making subject to site-specific environmental conditions and takes into consideration heterogeneity and interdependencies among agents and their environment. This is very important in large/diverse regions (such as MT) where the use of average indicators might lead to ineffective policy interventions (e.g., a policy beneficial for typical agents but unfavorable for other agents).

Our ABM was implemented using the software package Mathematical Programming-based Multi-Agent Systems (MPMAS). MPMAS uses whole-farm mathematical programming (MP) to simulate farmer decision-making in three stages: (1) investment decision, which occurs at the beginning of a cropping season when agents decide, for example, which machinery to buy; (2) production decision, which occurs before sowing, when agents decide which crops to grow; and (3) consumption decision, which occurs after harvest, when agents decide how much to sell, withdraw or save for future periods. In every simulation period, which corresponds to one real-world agricultural year, MPMAS maximizes model agent’s expected farm income according to its individual land, labor, machinery, and cash endowments as well as site-specific constraints (e.g., soil and weather characteristics) for each scenario and model repetition. At the investment and production stages, agents in MPMAS plan according to expected local yields and prices; at the third decision stage (consumption), agents update their decision based on simulated crop yields and current crop prices. The ODD (Overview, Design concepts, and Details) protocol describing MPMAS software architecture and equations can be found in Schreinemachers and Berger (2011).

The second component of our IA application is the process-based MOdel for NItrogen and CArbon in agro-ecosystems (MONICA). MONICA has been used to simulate crop yield responses to different soil types, cultivars, nitrogen fertilization rates, sowing dates, management practices, and climatic conditions (Hampf et al. 2018; Battisti et al. 2017a; Nendel et al. 2014). A detailed description of MONICA and its specification can be found in Nendel et al. (2011). For this study, MONICA was parameterized to five macro-regions, four soil types, fifteen years, four crops (soybean, maize, cotton, and sunflower), three soybean maturity groups, several nitrogen levels (five for maize, seven for cotton, and five for sunflower) and several sowing dates (four for soybean and maize, and five for cotton and sunflower).

MONICA calibration for soybean and maize was done using farm-level data from 32 different municipalities between 2007 and 2013, with 2527 observations for soybean and 576 for maize (Associação dos Produtores de Soja e Milho do Estado de Mato Grosso 2018). Soybean cultivars were subdivided into maturity groups (MG): cultivars with a MG of 6.5-7.4 were classified as MG VII, cultivars with a MG of 7.5-8.4 as mG V III and cultivars with a MG of 8.5-9.4 as MG IX, resulting in 130, 719, 1678 observations for soybean MG VII, MG VIII and MG IX, respectively. Cotton was calibrated using an unpublished survey from Céleres with 175 yield observations at farm level from 2010 to 2013 (Consultoria Focada na Análise do Agronegócio 2018). Field trials testing the performance of eight different sunflower cultivars on two different experimental sites in Campo Novo do Parecis between 2013 and 2015 were used for sunflower calibration (Birck et al. 2017). A random sample of two third of the datasets were used for calibration purposes and one third for model validation (see section 5.3.1). Crop cultivars were calibrated based on observed climate data from five different meteorological stations in MT (Canarana, Diamantino, Matupá, Poxoreo and Sapezal), containing daily weather records of temperature, precipitation, radiation etc. between 1999 and 2015 (Instituto Nacional de Meteorologia 2017). Soil properties (e.g., silk, clay content, C/N ratio, bulk density) were then taken from the soil database of (Cooper et al. 2005).

The modeling approach of Carauta et al. (2017a) and Hampf et al. (2018) was extended in five aspects. First, we included sunflower as a new production activity. Second, we implemented agent interactions through the innovation diffusion module (with sunflower cultivation as the innovative agricultural practice). Third, new management practices for maize production were incorporated (low cost management for late sowing dates). Fourth, agricultural input prices as well as crop prices were updated to a more recent time series to capture mid-term effects. Last, given the availability of a recent weather dataset with a longer time frame (1999-2015), an extended and updated time series of crop yields was simulated.

Following the sampling procedure of Instituto Mato-Grossense de Economia Agropecuária (2010a), our model was parameterized for five macro-regions in MT (Northeast, Southeast, West, Mid-North and South Central), which produce almost the entire agricultural output of the state. Following the Monte Carlo sampling approach of Berger and Schreinemachers (2006), a statistically consistent agent population was created with 720 agents using empirical data from the latest Brazilian Agricultural Census (Brazilian Institute of Geography and Statistics 2006) and the agricultural survey of the Mato Grosso Institute of Agricultural Economics (Instituto Mato-Grossense de Economia Agropecuária 2016c). Crop production requirements correspond to the 2015/2016 cropping season and were estimated from several sources, such as (1) IMEA agro-economic survey (Instituto Mato-Grossense de Economia

Agropecuária 2016c), (2) field survey, and (3) local field experts. Four different soil types were identified and assigned to each model agent based on the official maps of the socio-ecological zoning produced by the Mato Grosso State Secretary of Planning (Secretaria de Estado de Planejamento e Coordenação Geral de Mato Grosso 2011).

Model agents can choose between multiple crops, crop rotation schemes, sowing dates, maturity groups, fertilization rates, seed varieties, management options, and soil types. Given the initial development stage of sunflower cultivation in MT and the lack of specific farm-level data, a field survey was carried out over a period of three months (April to June of 2016) to identify the main factors associated with the recent development of sunflower production and processing in MT. Production and post-harvest costs were estimated based on interviews with local experts: farmers, technical assistance providers, researchers, industry representatives, and seed dealers. In total, 27 semi-structured interviews were carried out in five municipalities (Campo Novo do Parecis, Brasnorte, Sapezal, Campos de Júlio, and Sorriso).

In total, 254 production activities were estimated and attributed to each model agent for each cropping season and scenario. Each agent's Mixed Integer Programming (MIP) specification contained 2,045 decision variables (including 182 integers) and 1,741 constraints, which MPMAS adapts and solves for each agent, decision stage, period, scenario, and design point (model repetition for uncertainty analysis). To avoid computational limitation and to speed up simulation run time, each MIP was solved using the IBM-CPLEX solver and parallel simulations were run on the high-performance computer cluster of the state of Baden-Württemberg, Germany.

5.2.3. Model features

Our simulations include region-specific socio-economic constraints. This means that agents in different regions can use different types of pesticides and can select different intensity levels of machinery use. Also, agents in different regions face different input/selling prices as well as different transportation costs. To capture mid-term effects of technology diffusion, local market prices were estimated from IMEA for each macro-region for a period of four years (2014-2017).

Furthermore, our production cost also considers crop variety and maturity group. As an example, different seed varieties require different pesticides, pesticide applications, and quantities. Similarly, varieties with longer maturity cycles require more pesticide applications.

Moreover, each agricultural practice requires different field operations, and each field operation has its own input, labor, and machinery requirements. Therefore, a crop calendar with a weekly resolution was created for each agricultural practice to capture the timing of agricultural activities as well as to simulate agents' resource allocation of machinery, agricultural inputs, and labor. Rules determining crop rotations were parameterized in the MP as constraints, which are also linked to the crop calendar. In total, our production costs include 165 agricultural inputs (e.g., fertilizers, seeds, herbicides, insecticides, and fungicides), 13 field operations (e.g., harrowing, ploughing, soil correction, weed control, sowing, spraying, and harvesting), and three post-harvest costs (transporting, processing and storing).

Model agents face different transportation costs, depending on the region where they are located, and on the crop is produced. Transportation costs are estimated as an average distance from farm gate to processing facility multiplied by a transport fee. Both indices (average distance and transport fee) were taken from Instituto Mato-Grossense de Economia Agropecuária (2016c) for each crop and region. Since sunflower processing facilities are located only in the West, transportation costs of sunflower for other regions increased by the distance between the respective municipalities.

Field operations are subjected to weather conditions. Thus, months with high precipitation have fewer field days, which then reduces the monthly supply of labor and machinery. Agents in our model can hire three types of labor (manager, machine operator, and field assistant), who may have permanent or temporary contracts. Farm owner is assumed to work as a manager, and each manager is assumed to be responsible for an area up to 3,000 hectares. There are 16 machine types included in the model, and five of them (e.g., different types of seeders and harvesters) can be rented (but with limited hours due to local market constraints). Agents can purchase machinery using their own funds or with governmental credit lines. Model agents can access several credit lines, which differ by interest rate, credit conditions, and the purpose of use. For financing input acquisition, model agents can choose from federal credit lines (usually with lower interest rate but restricted credit limit), resellers, or multinational enterprises. Farm agents can also access federal credit lines for machinery acquisition; a more unconstrained credit line is accessible (with a higher interest rate and short time span) as working capital and can be freely used (e.g., to pay wages, hire workers or buy additional inputs if needed).

Direct interactions between households are modeled through the technological innovation model feature, where agents share information about new technologies. The technology innovation model component is based on the theory of diffusion of innovations developed by Rogers (2003), and is described by . Agent interactions are implemented as a frequency-dependent contagion effect: the more agents adopt a technology, the more it becomes accessible to others. The agent population is subdivided into five adopter categories (innovators, early adopters, early majority, late majority, and laggards). In the beginning, only innovators have access to the new technology. Only when agents in the more innovative segment have adopted the new technology, it becomes accessible to agents in the less innovative segment.

Once an agent adopts a new technology (e.g., sunflower) or a complex production system (e.g., cotton) for the first time, it faces learning costs that were parameterized to simulate (1) the initial investment with specialized machinery and/or (2) the yield gap between a novice and an experienced farmer. The learning curve is expressed in terms of relative yield and was estimated with local experts and technical advisors. For sunflower, the relative yield is 85%, 90%, 95%, 97.5%, and for cotton 80%, 85%, 90%, 95% at the first four years and 100% at the following years. In our study, we have not considered synergy effects (e.g., reduction of nematode population after sunflower adoption) on soybean-sunflower rotation schemes since farm-level data on synergy effects (e.g., nematode population) is currently not available for agricultural fields in MT.

Model agents pay different types of taxes and charges related to production, sales, and land use. Taxes were included in MPMAS following the current legislation. If farm agents have more cash than they need, they can receive interest for short-term deposits. At the end of each simulation period, each agent must secure a minimum consumption threshold to fulfill his livelihood. Otherwise, it will be excluded from the simulation. Furthermore, if there is a cash surplus, each agent spends a share of its income on consumption (that depends on the performance of the household enterprise). The remaining cash is carried over to the next period to continue the production cycle.

At the beginning of the simulation, land (owned and rented) is assigned to each agent according to the latest agricultural census (Brazilian Institute of Geography and Statistics 2006). If an agent rents land, it must pay the rent until the end of the renting contract. In exceptional cases, an agent might cancel a renting contract before it is completed (e.g., cash reserve is insufficient, and all credit limits were reached), but receives a utility penalty in its objective function. Model agents can also rent out their own land for a discounted price lower than the market price (this prevents agents with lower gross-margins to rent out whole farms since there is no information about how much land can be rented out).

5.3. Model validation and simulation experiments

5.3.1. Model verification and validation

At the model verification stage, structured verification tests were done to check if the code has been thoroughly tested for programming errors and to evaluate whether our model performs as designed. A face validation of model and simulation results was done with local experts and professionals with in-depth knowledge of MT. To that, we have established partnerships with key institutions in MT, such as the Brazilian Agricultural Research Corporation (EMBRAPA), Mato Grosso Agriculture Economic Institute (IMEA), Federal University of Mato Grosso (UFMT), Federal Institute of Mato Grosso (IFMT), and Soybean and Maize Producers Association of Mato Grosso (APROSOJA).

At the model validation stage, we evaluated how well simulated values match with the corresponding observed values. We assessed the reliability of our simulations in both models, MPMAS and MONICA. Since our MPMAS application simulates both the decision of individual farms and the agricultural land-use patterns of the study area as a whole, we used two benchmarks for model validation: (1) for farm-level validation, we compared the simulated land use of single farms with typical farms from IMEA's survey (Instituto Mato-Grossense de Economia Agropecuária 2016c); (2) for regional-level validation, we compared our simulated land use (a weighted aggregate of the representative farms) with the ones observed in the corresponding agricultural survey from the Brazilian Institute of Geography and Statistics (Brazilian Institute of Geography and Statistics 2018).

As suggested by Troost and Berger (2015), to avoid overfitting and deterioration of model's out-of-sample properties, we did not calibrate the model for a perfect fit but instead assessed model efficiency by evaluating the full space spanned by the uncertain model parameters. Table 5.1 presents the model's goodness-of-fit for MPMAS simulations at farm and regional levels, calculated based on standardized absolute errors (ESAE). As it can be seen from the table, the results of our empirical validation suggest a very good model performance, with validation indices close to unity on both levels of aggregation.

Table 5.1 *MPMAS model validation: distribution of ESAE over Sobol' sequence.*

	Average	Min	Max
Farm Level			
Typical Farm 1	0.9677	0.9936	0.9009
Typical Farm 2	0.8273	0.9009	0.7696
Typical Farm 3	0.8796	0.9490	0.8098
Typical Farm 4	0.5455	0.5457	0.5455
Typical Farm 5	0.9334	0.9979	0.7770
Typical Farm 6	0.5983	0.6449	0.5394
Typical Farm 7	0.7096	0.8134	0.6649
Typical Farm 8	0.7327	0.7348	0.7184
Typical Farm 9	0.5791	0.6153	0.5273
Typical Farm 10	0.7553	0.8586	0.6665
Typical Farm 11	0.7263	0.7585	0.7074
Regional Level			
West	0.6587	0.6741	0.6438
Mid-North	0.9105	0.9217	0.8981
Southeast	0.9039	0.9140	0.8927
South Central	0.8275	0.8299	0.8247
Northeast	0.9718	0.9933	0.9376

To evaluate the predictive performance of MONICA, simulated crop yields were compared to observed yields at farm level. Observed crop yields for soybean, maize, cotton, and sunflower were taken from datasets described in section 5.2.2. To test the performance of MONICA, the following evaluation indices were calculated and are shown in the Table 5.2: root mean square error (RMSE), normalized RMSE (rRMSE), and Willmot´s index of agreement (d). The normalized RMSE ranges between 16.3 for soybean MG VIII and 28.9 for cotton lint, indicating a reasonable performance of MONICA.

Table 5.2 *MONICA model validation.*

Crops	RMSE	NRMSE	d
Soybean MG VII	779.72	14.8	0.38
Soybean MG VIII	678.58	14.7	0.35
Soybean MG VIIII	678.58	14.7	0.35
Maize	1866.91	19.9	0.42
Cotton	359.64	36.9	0.21
Sunflower	332.2	25.6	0.66

Note: RMSE = root mean square error, rRMSE = normalized RMSE, and d = Willmot´s index of agreement.

5.3.2. Simulation experiments

The impact analysis was done by comparing a baseline scenario [With Sunflower] – which reflects the situation in which, at the beginning of the simulation, only innovators have access to sunflower cultivation (but may decide to not adopt it) – with a counterfactual scenario [Without Sunflower] where no sunflower is made available to model agents. To fully capture the technological diffusion process, we ran MPMAS and MONICA models over a simulation period of 15 years.

5.3.3. Uncertainty analysis (UA)

Since simulation models are usually subjected to uncertainty associated with model inputs (parameters and exogenous variables), an UA was carried out to verify the robustness of our simulation results. We followed the approach of Troost and Berger (2015) and Berger et al. (2017) and identified 18 uncertainty parameters, which can be grouped into four categories: crop prices, input prices, crop yields, and other model parameters. Local prices and yields in MT are, usually, highly correlated (e.g., prices and yields due to their relationship with climatic conditions and forces of supply and demand; crop prices and input prices due to a common dependence on US dollar exchange rates). To preserve the observed correlations in the sampling procedure, we did not sample yields and prices independently but instead sampled complete price/yield vectors for one year from the complete set of local market prices and yields of all years form the local data observed in MT (available for 2012 to 2017).

Local prices were corrected for inflation and market trends. We applied the Sobol' sequence, a quasi-random sampling that tends to converge faster and generates samples more uniformly (Tarantola et al. 2012). Our simulations were run for 60 repetitions, and each scenario was simulated using the same Sobol' sequence of parameters to isolate the scenario effect on each individual agent from any variation in other parameters (Troost and Berger 2015). As Figure 5.1 shows, the test for model convergence indicates that the mean and 5th and 95th percentile of simulated sunflower land use rapidly converges to stable values, indicating that 60 repetitions are enough in our case to generate robust results.

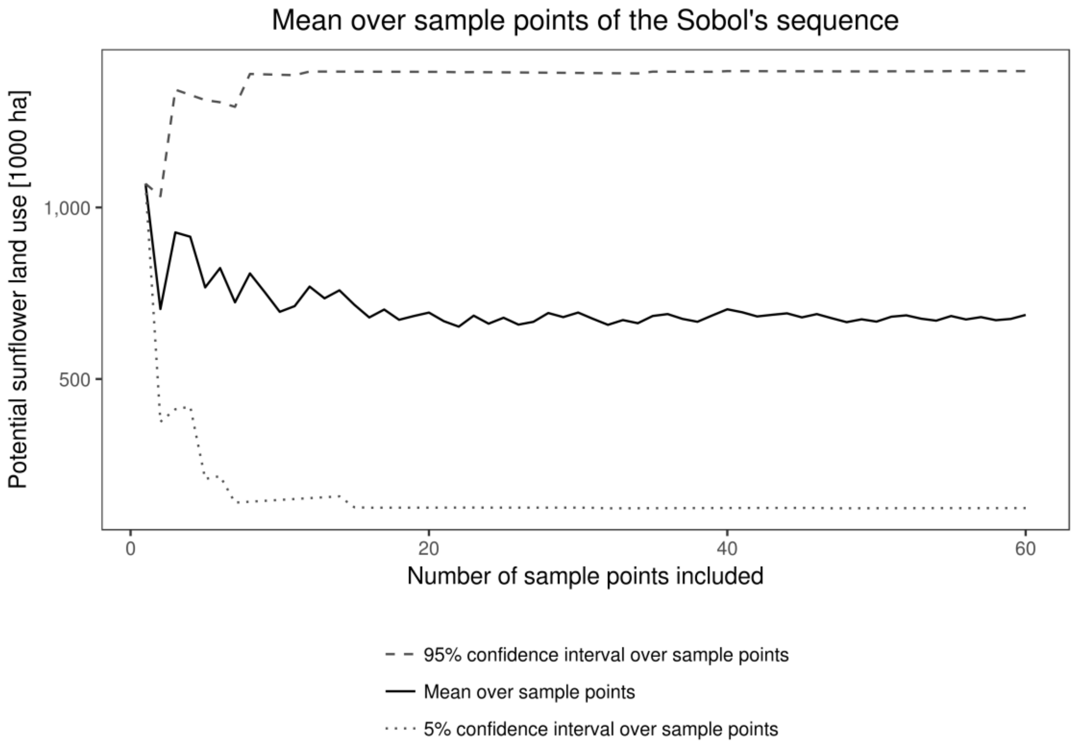


Figure 5.1 *Convergence of simulated (potential) sunflower land-use over Sobol' sequence*

5.4. Results

5.4.1. Sunflower diffusion in MT

Figure 5.2 shows the simulated diffusion curves for sunflower in MT for all repetitions over a 15-year period. The adoption rate is estimated as a cumulative adoption (percentage of farmers) over time. Each curve represents one model repetition, which is characterized by a set of model parameters that influences the farmer's decision-making. As shown in Figure 5.2, the diffusion curves converge to six rather clearly separated groups (A, B, C, D, E and F) that are associated with a set of local prices and yields observed for a specific year in MT (section

5.3.3). The technology diffusion process took approximately five simulation years and reached a maximum adoption rate of 32% at some model repetitions [Group A] and a minimum adoption rate of 12% at other repetitions [Group F].

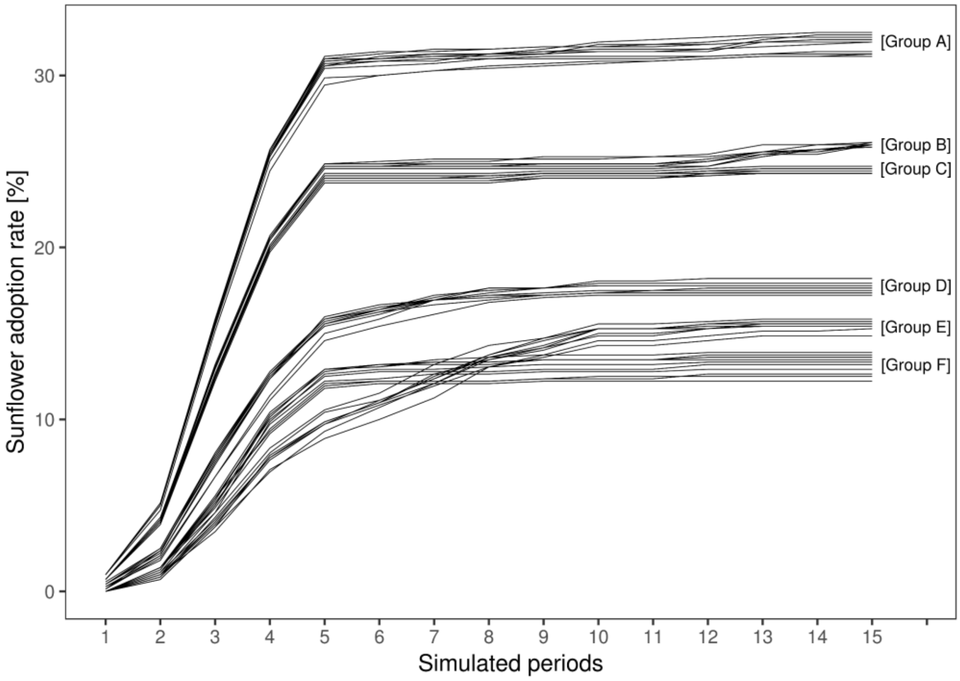
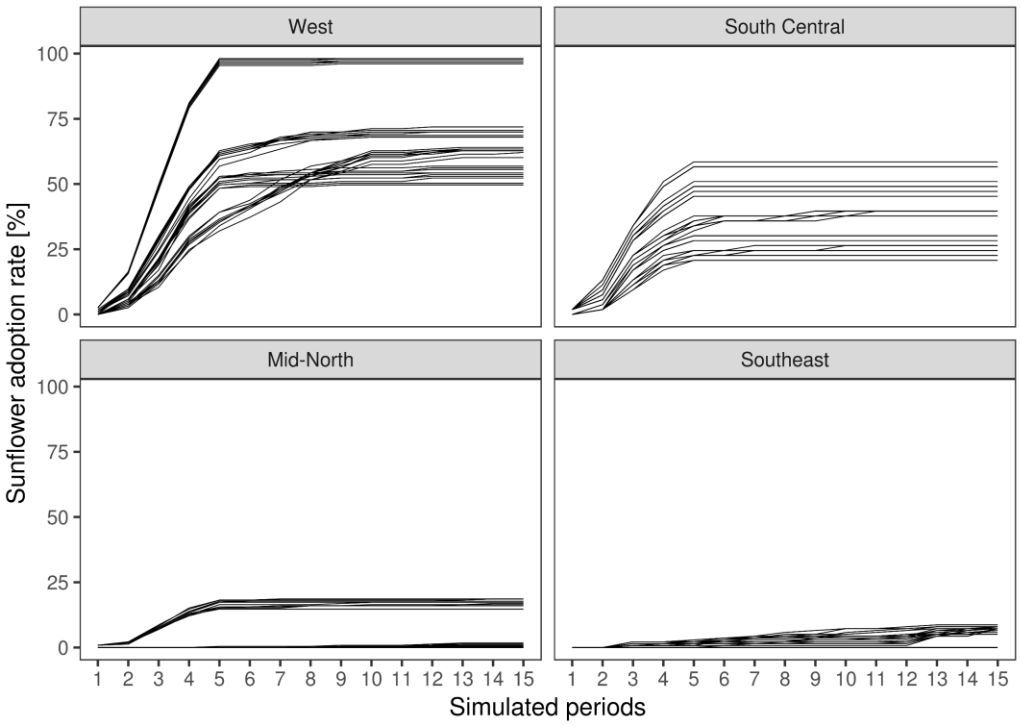


Figure 5.2 *Sunflower innovation diffusion in Mato Grosso.*

A closer investigation at the six outcome groups reveals that sunflower adoption showed a significant variation due to aleatory uncertainty (represented by a complete set of prices and yields observed in MT). Groups A, B, and C are associated with agent's expectation of favorable conditions for sunflower production (an increase on sunflower price and/or yields) combined with unfavorable expectations for maize or cotton (a decrease on price and/or yields). Group E is associated with favorable market expectations for maize and group F with favorable conditions for maize and cotton in combination with unfavorable conditions for sunflower.

5.4.2. Sunflower diffusion at regional-level

The innovation diffusion of sunflower at the regional level is represented in Figure 5.3. The simulation results indicate that the highest adoption share was achieved in the West, whereas the Northeast had no adoption. Our simulation shows a negative correlation between sunflower adoption and transportation costs. Since the processing facilities are located in the West, farmers in other regions face higher transportation costs because the distance to the processing facility is larger. In some repetitions, the whole agent population in West adopted sunflower, while in other repetitions the minimum adoption rate was 50% in that region.



Note: Region Northeast is not shown since model agents in this region did not adopt sunflower.

Figure 5.3 *Sunflower innovation diffusion at regional-level.*

5.4.3. Land-use trade-offs

Figure 5.4 presents the land-use trade-offs in the second crop season by comparing the land-use allocation between the scenarios [Without Sunflower] and [With Sunflower]. Land use share is averaged over all farms and grouped into attractor groups (from A to F). Figure 5.4 shows groups A and F while other groups are presented in the appendix. Our simulations show that the main competing crop for sunflower is maize, which had its land-use share reduced in the West and South Central (regions with the largest share of sunflower cultivation). Interestingly, regions with higher sunflower adoption also reduced fallow land use in the second season.

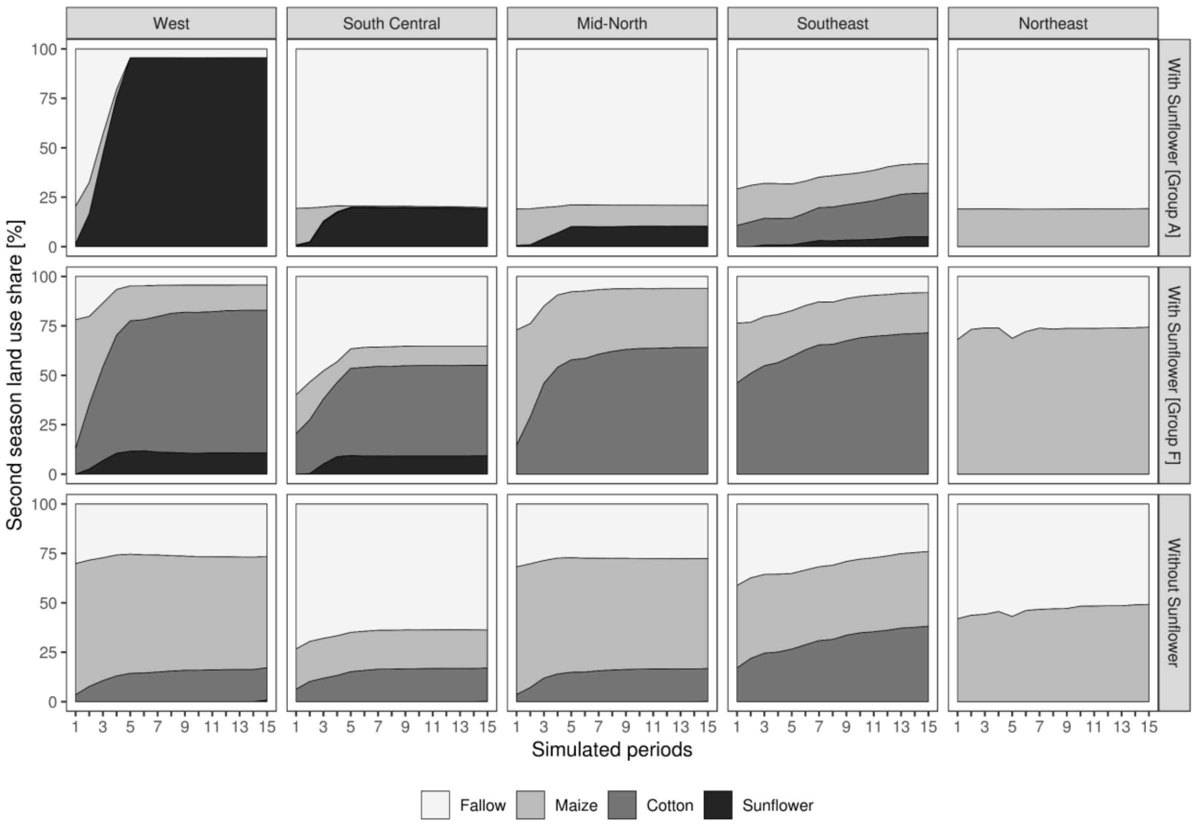


Figure 5.4 *Land-use allocation in the second cropping season*

A substantial intensification of land use could be observed after the introduction of sunflower - together with a decrease in maize land use – in cases where higher sunflower prices and yields were observed [Group A]. On the other hand, when conditions favored cotton and maize production [Case F], simulation results showed a slight increase of sunflower adoption and a significant increase of cotton land use. To further investigate the land-use trade-offs in the second season, the simulated land-use was disaggregated for all sowing dates. Figure 5.5 shows the land-use difference between [Without Sunflower] and [With Sunflower] scenarios over all repetitions and years (upscaled for Mato Grosso).

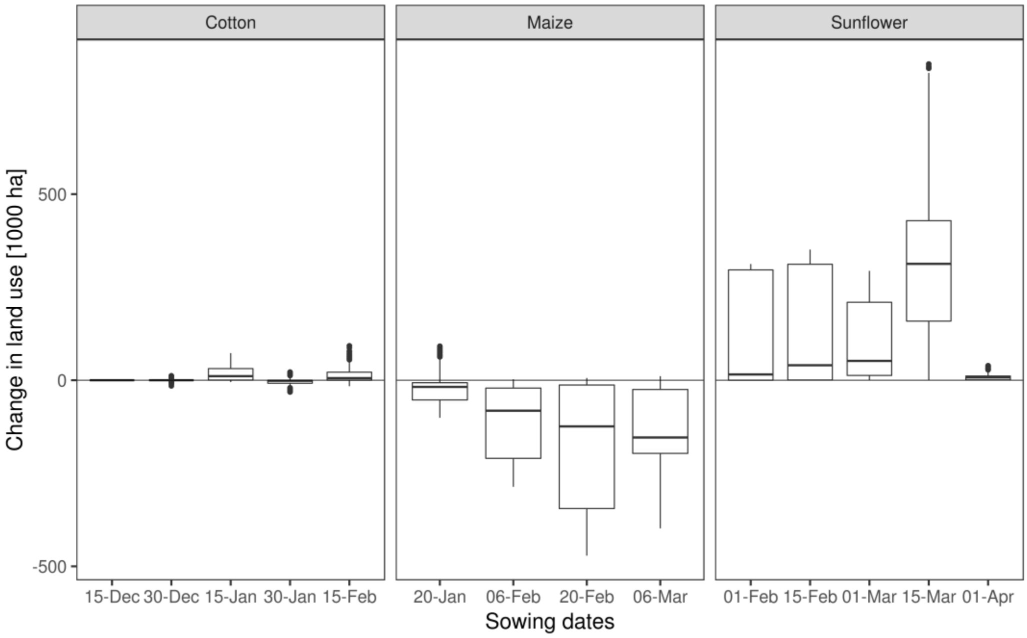


Figure 5.5 *Simulated land-use of cotton, maize, and sunflower upscaled to Mato Grosso using IBGE sampling weights for land use*

Most sunflower adopters chose to sow it on 15-Mar, when the maize sowing window is already over. Similarly, the most significant reduction in maize land use was also recorded on the latest sowing dates (20-Feb and 06-Mar) since sunflower was more profitable than later-sown maize. Differences in yields due to changes in precipitation can explain the more substantial reduction of maize land use at 20-Feb and 06-Mar (since maize yields are considerably lower in March in comparison to January/February, whereas sunflower yields decrease mainly after mid-March). Moreover, a slight increase in cotton land use was observed after the introduction of sunflower, which can be explained by its high economic returns (in comparison to maize and sunflower).

5.4.4. Potential production of sunflower in MT

To simulate the potential sunflower production in MT, we allowed farm agents to produce any amount of sunflower that would maximize their expected gross margin, independent of current sunflower processing capacity. Figure 5.6 depicts the current processing capacity (approximately 300,000 tons per year) as a dashed line and the potential sunflower production simulated for MT as solid lines (over a 15-year horizon and all model runs). A substantial variation can be observed between years and model repetitions. Variation from model repetitions can be explained by different agent's expectation of prices and yields while different weather conditions explain variation between cropping seasons.

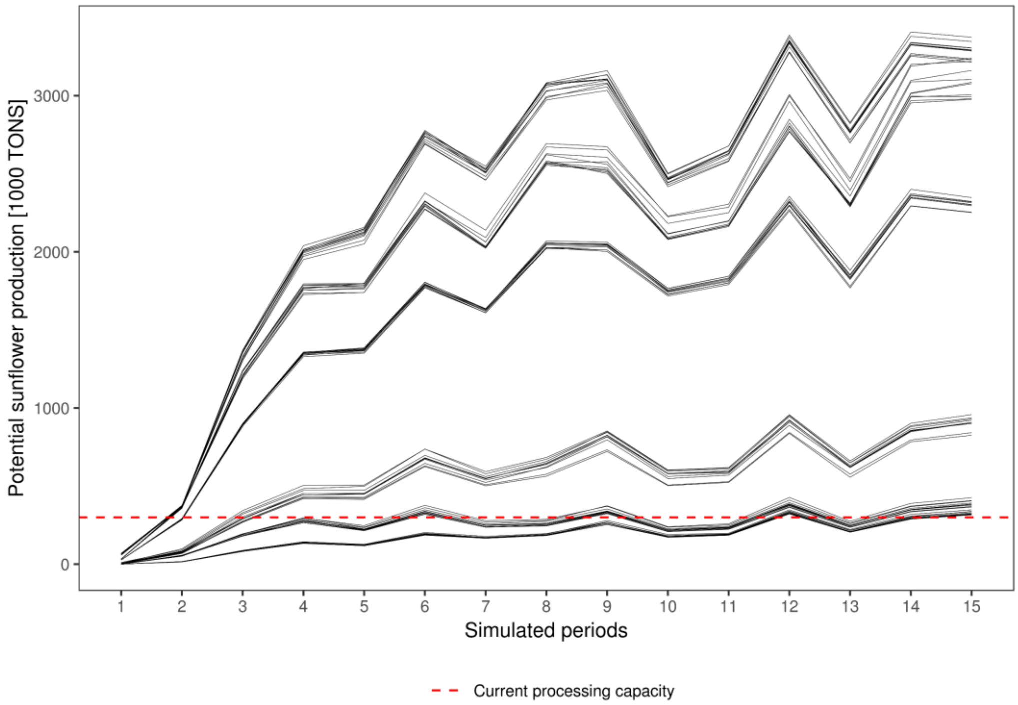
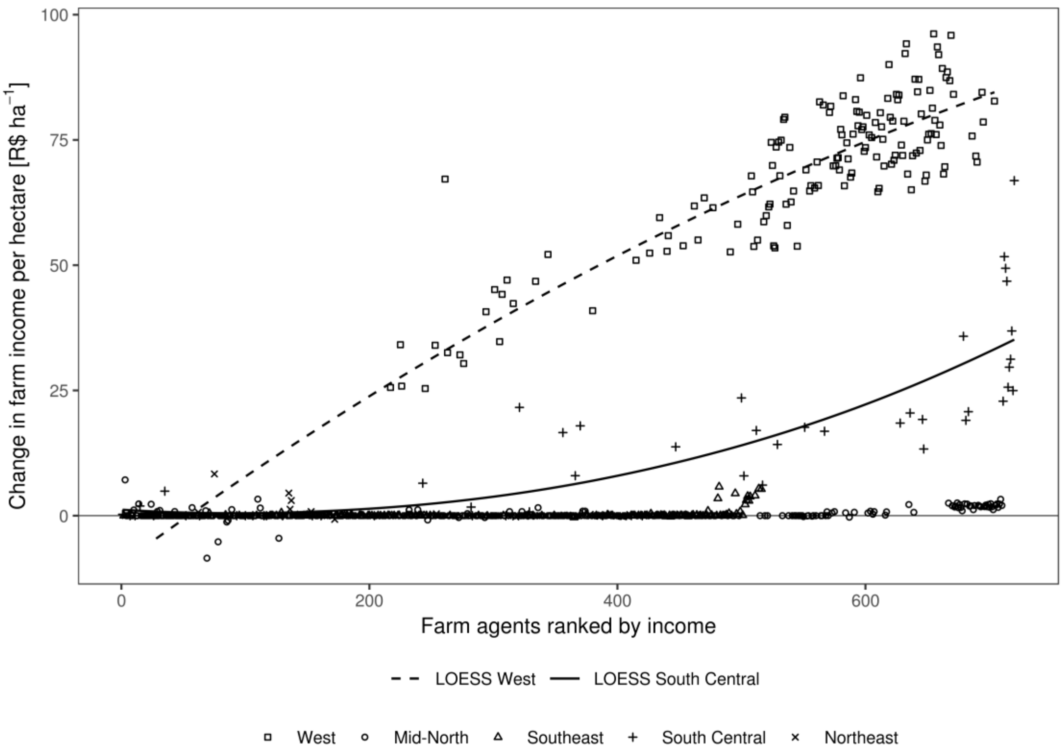


Figure 5.6 *Potential production of sunflower in Mato Grosso (upscaled using IBGE sampling weights for land use)*

5.4.5. Impact of sunflower adoption on farm income

To investigate the impact of sunflower adoption on farm-level income, we compared farm income between both scenarios (with and without sunflower). Figure 5.7 ranks individual agents by their average income per hectare in the counterfactual scenario [Without Sunflower] over all repetitions and years. Our simulation indicates a positive impact of sunflower on farm income. Moreover, a closer look at the regional level reveals that its impact is stronger in the regions West and South Central due to their proximity to the processing facility.



Note: Individual agent incomes were averaged over all repetitions and years and then ranked by income in the counterfactual scenario [Without Sunflower]. LOESS span (amount of smoothing) = 2.

Figure 5.7 *Income change in the baseline [With Sunflower] compared to counterfactual scenario [Without Sunflower]*

5.4.6. Economic impact of sunflower adoption at regional-level

Table 5.3 shows the impact of sunflower diffusion at MT and regional level, considering all 60 repetitions and 15 years that were simulated for both scenarios (e.g., pairwise comparisons of farm income for each agent). The impact of sunflower adoption is measured by relative changes in income and income variance. The average and variance of income was computed for each agent in each model repetition and, to control for positive trends in income, the variance of income was calculated from deviations around a three-year moving average rather than a plain average. Results show a high incidence of “economic opportunity”, where the introduction of sunflower increased average income with higher variance, as well as high incidence of “ideal outcome”, where increased income was reported with equal or lower variance. In approximately a quarter of cases, sunflower adopters reported higher average income with lower variance (“ideal outcome”) and, in 70% of the cases, the incidence of higher average income with higher variance (“economic opportunity”).

Table 5.3 *Economic outcome after sunflower adoption*

Indicator	Mato Grosso		West		South Central		Mid-North		Southeast	
	All agents	Only adopters	All agents	Only adopters	All agents	Only adopters	All agents	Only adopters	All agents	Only adopters
"Ideal outcome" Incidence of higher average income with equal or lower variance (%)	6%	25%	21%	26%	2%	5%	2%	57%	1%	45%
"Stabilization" Incidence of identical average income with lower variance (%)	0%	1%	1%	1%	0%	0%	0%	0%	0%	0%
"Economic opportunity" Incidence of higher average income together with higher variance (%)	15%	70%	56%	69%	37%	90%	1%	31%	1%	42%
"Without uptake" Incidence of identical average income and variance (%)	78%	3%	22%	2%	59%	1%	96%	8%	97%	4%
"Costly stabilization" Incidence of lower average income with lower variance (%)	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
"Maladaptation" Incidence of equal or lower income with higher variance plus incidence of lower income with equal variance (%)	1%	2%	1%	2%	1%	3%	0%	3%	0%	7%

Note: "Incidence of higher average income with lower variance" is computed as follows: for all agents in all repetitions, the number of cases was counted where an individual agent increased its average income after the introduction of sunflower [With Sunflower] over 15 years against the counterfactual scenario [Without Sunflower] while at the same time decreasing the variance of income around the three-year moving average. The number of these cases was then related to the total number of all simulated cases. All other incidences were computed analogously. Region Northeast is not shown since it had no sunflower adoption.

5.5. Discussion

This study followed an integrated modeling approach to simulate the diffusion of sunflower in MT. Our simulation results indicate that sunflower adoption reached about one-third of the agent population, which suggest that sunflower could be a potential alternative to current farming systems in MT. Furthermore, our analysis at the regional level shows that sunflower adoption is strongly constrained by the distance between farm gate and processing facility. In other words, building processing facilities in other regions might be a necessary condition for sunflower diffusion in MT – as Sousa et al. (2018) pointed out, the development of the sunflower sector in West was driven by the establishment of processing facilities in Campo Novo do Parecis.

On the other hand, another finding was that farm proximity to a processing facility is not a sufficient condition to sunflower diffusion. A closer look at the agent's decision-making reveals that sunflower land use is strongly associated with the agent's expectation of prices and yields. A higher adoption was achieved in model repetitions where a combination of (1) favorable conditions for sunflower cultivation and (2) unfavorable conditions for maize or cotton production were expected. This result underlines the importance of considering different future price developments into account in integrated assessment studies of technology diffusion.

Our impact assessment reveals that the adoption of sunflower leads to land-use intensification. Rather than expansion, land-use intensification might slow down or even prevent the clearing of native vegetation for agricultural purposes and, therefore, reduce the impact on climate change driven by land-use change (Matsuura et al. 2017). A possible explanation for this result is the extension of the sowing window in the second season created by sunflower adoption. Since sunflower is more tolerant to water stress than maize, agents manage to increase cropping intensity in March (a period in which maize yields are significantly affected by water deficit).

Our results, as shown in Figure 5.6, indicate that there is additional sunflower production potential in MT and that it may be worthwhile to extend processing capacity to absorb that potential. In contrast, Sousa et al. (2018) observed that existing sunflower processing facilities in MT have operated below processing capacity due to the initial development stage of sunflower sector. For this reason, the future increase in sunflower processing capacity should be accompanied by investments in the development of pest and disease control mechanisms (adapted to sunflower) and seeds adapted to MT conditions.

We also captured the economic trade-offs in double-crop production systems in MT. In terms of sunflower cropland, we found small evidence of competition with cotton land use. Actually, in some cases, the introduction of sunflower enabled farm agents to increase cotton land use. On the other hand, we found strong evidence of competition with maize. Taken together, these findings suggest that sunflower can be a potential alternative for cropping season with unfavorable production conditions for maize since the alternative option, switching to cotton, requires high amounts of capital and expertise.

The results of our simulations suggest that sunflower indeed contributed to increased farm income. In about 22% of all cases (720 agents * 60 repetitions * 15 years) sunflower was adopted by model agents. In many of these cases, adopters experienced an increase in farm income (although in most of the cases an increase in income variance was also observed). In contrast, we also found a low incidence of “maladaptation” (better off not adopting sunflower cultivation due to equal or lower income with higher or equal variance) and “costly stabilization” (lower average income with lower variance), which suggest that the diffusion of sunflower generally benefited farmers. Our uncertainty analysis additionally shows that maladaptation occurred more often in years where actual sunflower yields were lower than expected ones. Given that sunflower adoption enabled, in some cases, model agents to cultivate more cotton, we found out few cases of maladaptation related to frustrated cotton yield expectation.

5.6. Conclusion

The state of Mato Grosso is a globally important producer of grains and beef. Its agricultural success is a result of favorable climatic/landscape conditions, current farm structures (large-scale commercial agriculture), and the diffusion of new technologies. This paper brings important contributions to understand the double-cropping production systems in MT, mainly by evaluating the impact of sunflower diffusion, a promising alternative to current rotation schemes. To the best of our knowledge, this is the first study in MT to estimate the potential sunflower production and to assess its impact at farm level. This study has shown that there is a substantial potential for sunflower cultivation in MT and that sunflower adoption had a positive impact on farm income.

Our IA approach also allowed us to identify bottlenecks for sunflower diffusion. The results of this study show that the distance from farm gate to processing facility had a significant impact on sunflower adoption. We also found out that in most cases sunflower adoption improved farm income, and only in a few cases it led to maladaptation. Another relevant finding was that expected crop prices and yields play a crucial role in agents' decision-making and, consequently, on sunflower land use. Taken together, these findings suggest that sunflower can be an alternative agricultural practice because it can increase farm income and land use intensification. Furthermore, since it expands the sowing window, it can be a potential strategy for climate change adaptation, giving more flexibility on field operations and reducing risk to water stress.

Since our focus was on simulating potential sunflower adoption and production, we did not consider (yet) the current limited processing capacity. We plan to tackle this in a subsequent analysis by implementing a model extension that represents the interactions between processing facilities and farmers. Similarly, market response to national and global maize production decrease and sunflower production increase will need to be addressed to confirm the results. The current model did not yet take projected yield effects of climate change into account, but the model system is readily usable for assessing the potential of sunflower production as a potential adaptation to climate change in a next step.

Chapter 6. Why should farmers in Brazil change to integrated agricultural production systems?

Ianna Raissa Moreira Dantas, Marcelo Carauta

This chapter has been published[8] in the International Journal of Agriculture and Environmental Research in December 2016.

Abstract

Increasing demand for food relies on sustainable agriculture practices to feed the worldwide population. Brazil, as a key producer of agricultural commodities, plays an important role in overcoming environmental challenges and promoting sustainability. In this context, integrated agricultural production systems (IAPS) rise as an alternative to increasing agricultural efficiency due to its potential benefits such as soil fertility, higher productivity, lower use of agrochemicals, interruption of pest and disease cycles as well as income diversification. The main goal stands for strategically changing land use by integrating sustainable production of agricultural, livestock and forestry activities in the same area, through intercropping, succession or rotation, by seeking the synergistic effects between each production system component. Despite current efforts from the Brazilian Government to boost IAPS adoption, those systems have not yet been adopted on a large scale. Therefore, this study aims to identify potential synergy effects, which are more likely to be explored by Brazilian farmers. Subsequently, this paper provides insights into farmers' decision making and comprehension about the interaction of IAPS components.

6.1. Introduction

The Brazilian agricultural sector has propped up the nation amongst the ten worldwide economies (Organisation for Economic Co-operation and Development and Food and Agricultural Organization of the United Nations 2015). Ongoing investments in technology stimulated agricultural production over 76 million hectares of arable land, boosting production

[8] Dantas, I., Carauta, M., 2016. Why should farmers in Brazil change to Integrated Agricultural Production Systems? International Journal of Agriculture and Environmental Research 2 (6), 18.

over the last 30 years (Rada and Valdes 2012). Agricultural commodities summed up 36% of the total exports, strengthening the importance of Brazil towards the international market (Organisation for Economic Co-operation and Development and Food and Agricultural Organization of the United Nations 2015).

According to Organisation for Economic Co-operation and Development and Food and Agricultural Organization of the United Nations (2015), the agricultural frontier expansion in the central-west and northern regions is key for production of commodities for international markets, such as grains, sugar, beef and tropical fruits. In this context, the State of Mato Grosso is the biggest producer of grains and holds the largest cattle herd in Brazil (Brazilian National Supply Company 2018). For the harvest year of 2015/2016, the state of Mato Grosso produced 24.42% of total Brazilian agricultural commodities, 24% of maize and 28% of soy (Brazilian National Supply Company 2016a).

Intensifying monoculture of grains and livestock under plow-based agriculture in the Cerrado and Southern Amazon triggered massive environmental degradation. Despite the high levels of deforestation (Organisation for Economic Co-operation and Development and Food and Agricultural Organization of the United Nations 2015), the lack of conservation practices deals with erosion, loss of soil nutrients, range degradations (Macedo 2009), higher incidence of pests (Balbino et al. 2011), as well as high emissions of carbon dioxide (Sawyer 2009).

Subsequently, no-tillage system and integrated agricultural production systems (IAPS) emerged as alternative production systems thought to ease environmental challenges, increase yield and, maintain Brazil’s top rank internationally, by promoting long-term sustainable agriculture (Macedo 2009).

In this context, IAPS can be defined as a wide set of sustainable systems promoting the combination of agricultural activities that enable complex interactions among soil-plant-animal and atmosphere. The system supports husbandry and agricultural production in the same productive space (Anghinoni et al. 2013). The Brazilian scientific community perceives IAPS as part of conservation agriculture that along with no-till systems and crop rotation result in a series of environmental and economic benefits (Anghinoni et al. 2013).

Although IAPS are currently acknowledged as innovation, Roman scripts dated from the century I a. C. documented the use of integrated techniques to grow fruits and timber (Balbino et al. 2011). In the tropics, prior to European colonization, indigenous communities applied techniques of cultivating different crops altogether. European immigrants, in turn, cultivated different species adapted accordingly to tropical and subtropical characteristics. For instance, in the state of Rio Grande do Sul, in the southern region of Brazil, different models of IAPS have been used for decades (Balbino et al. 2012).

However, during the second half of the twentieth century, the Green Revolution changed the agricultural production system in Brazil. The goal was to increase food supply by investing in large-scale agriculture and intensifying production into mono-cropping models. This system was consequently criticized for triggering environmental and economic impacts and due to the increasing aim for sustainable agriculture.

Brazil hosts several types of IAPS (Ministério do Meio Ambiente 2015) to produce fruits and vegetables (Zambolim et al. 2009) and even aquaculture (Marchezan et al. 2006). Nevertheless, models of integration of crop-livestock-forestry have been the target of investments to produce beef and cash crops such as soybeans, cotton, maize, eucalyptus and rice (Anghinoni et al. 2013).

Integrated crop-livestock (iCL) and integrated crop-livestock-forestry (iCLF) systems were included in the national Low Carbon Emission Agricultural Plan (ABC plan). The ABC plan aims to reduce carbon emissions in the agricultural sector by offering credit lines to stimulate low carbon agricultural practices such as no-till agriculture, range recovering and, IS (Carvalho et al. 2014).

Although there is historical evidence of the economic and environmental benefits of IAPS, it is still a challenge to stimulate an increasing adoption of IAPS in Brazil. It is especially due to the asymmetry of information about these systems, bureaucracy to access agricultural loans (Gil et al. 2015) and also lack scientific studies of the economic and environmental gains generated by IAPS (Flores 2004). Additionally, it is costly and time-consuming to run experiments and computing results, insofar as research needs long-term investments to provide reliable outcomes from IAPS (Macedo 2009). The present work, therefore, aims at providing qualitative and quantitative evidence of why Brazilian producers should adopt integrated models such as crop-livestock (iCL), integrated crop-livestock forestry (iCLF), integrated crop-forestry (iCF) and integrated livestock-forestry (iLF).

6.2. Integrated agricultural production systems in Brazil

The increasing demand for agricultural goods relies on sustainable agriculture practices to feed the worldwide population (Carvalho et al. 2014). This way, IAPS rise as an alternative to ease environmental problems and increase agricultural efficiency (Carvalho et al. 2014; Gonçalves and Franchini 2007; Macedo 2009). It is because they are part of conservation agriculture (Balbino et al. 2012; Pariz et al. 2011) that, in turn, follows five premises:

1. "*Improving efficiency in the use of resources is crucial to sustainable agriculture*";
2. "*Sustainability requires direct action to conserve, protect and enhance natural resources*";
3. "*Agriculture that fails to protect and improve rural livelihoods, equity, and social well-being is unsustainable*";
4. "*Enhanced resilience of people, communities and ecosystems is key to sustainable agriculture*";
5. "*Sustainable food and agriculture require responsible and effective governance mechanisms*" (Balbino et al. 2012; Food and Agricultural Organization of the United Nations 2014).

According to Balbino et al. (2012), integration of crop-livestock-forestry elements, in their diverse set of arrangements, is defined as the diversification, rotation, and combination of agricultural activities in a common productive space. The elements become part of one single system that, due to synergy, improves production of all parts. The main goal stands for changing land use structure by integrating productive components which will maximize positive effects on the environment, increase productivity and recover natural resources in degraded areas (Balbino et al. 2012).

The integration incorporates several placement models (Gil et al. 2015) that are related in a matter of time or space. For the integration over time, agricultural activities rotate in the same area over the years, producing, in turn, a single output per year. On the other hand, the spatial integration enables the combination of different activities simultaneously in the same space. The integration of cash crops such as soybean, maize, cotton with beef and/or eucalyptus as well as nontimber products originates four predominant models of IAPS in Brazil: iCL, iFL, iCF, iCLF (Balbino et al. 2012; Gil et al. 2015).

6.2.1. Integrated crop-livestock systems (iCL)

The system aims at integrating different species of annual or perennial crops and grass to produce grains, animal feed and animals. Figure 6.1 exemplifies an iCL model in which crop and grass species rotate within four plots. Every harvest year a single plot produces a different product, either grain or grass for cattle ranching.

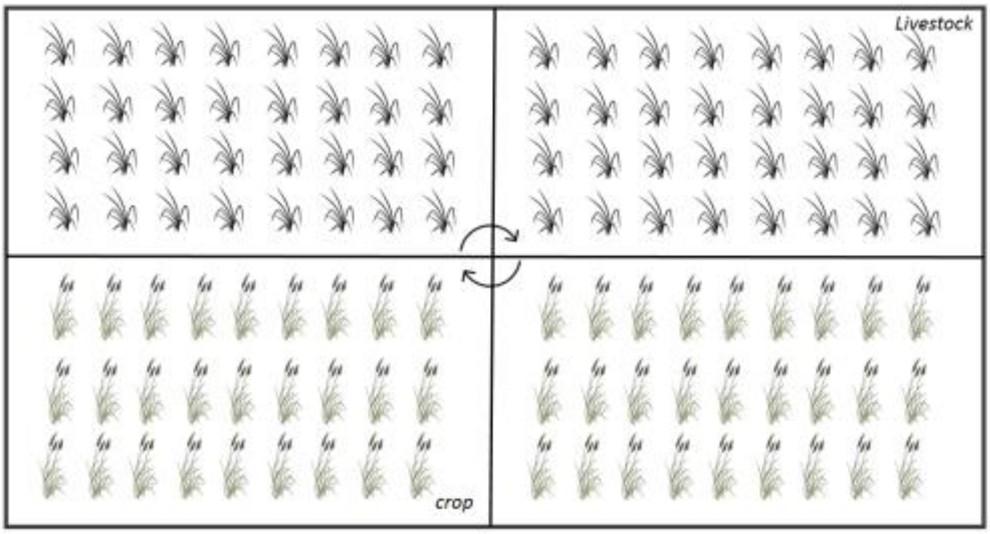


Figure 6.1 *Example of integrated crop livestock system*

6.2.2. Integrated forestry-livestock systems (iFL)

The system integrates forestry and grass species to produce timber and/or non-timber products, as well as animal feed and animal products. Figure 6.2 depicts integration in space of grass and forestry products, enabling pastures between forestry rows.

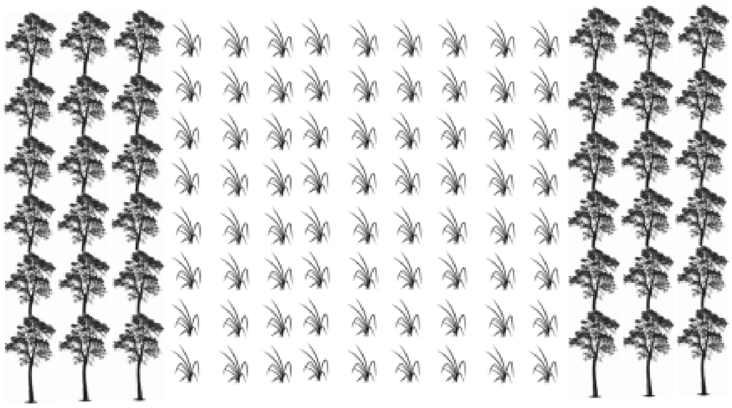


Figure 6.2 *Example of integrated forestry-livestock system*

6.2.3. Integrated crop-forestry systems (iCF)

The system integrates forestry and crop species to produce both timber and/or non-timber products and grains. Figure 6.3 illustrates an arrangement for iCF system. The model is similar to the one presented previously, however the aim is producing grains instead of fodder.

Figure 6.3 *Example of integrated crop-forestry system*

6.2.4. Integrated Crop-Livestock-Forestry systems (iCLF)

The system integrates forestry, crop and grass species to produce timber and/or non-timber products, grains, animal feed and animals. Among all models above, the iCLF system presents the highest level of complexity for combining three different activities. Figure 6.4 provides an example of iCLF design in which crops, and livestock are integrated in time and forestry integrated in space with both of them. In case crops and grasses are placed together, production may be jeopardized for possible cattle ranching in cropping areas. To avoid this competition, crop and livestock rotate over time in an area of forestry.

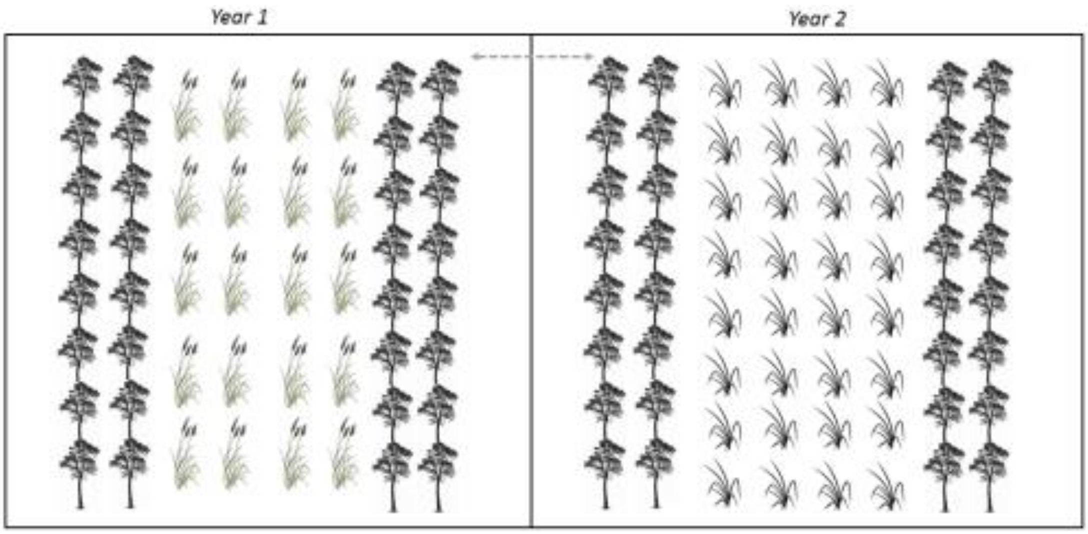


Figure 6.4 *Example of integrated crop-livestock-forestry system*

Integration models differ across regions according to climate, soil, farm size, own-funding, access to credits, technical assistance and market to purchase inputs, production outflow, level of expertise and land availability (Dias Filho 2007; Lourival Vilela et al. 2001).

The eventual rotation of crops and grass species is a common practice in many regions of Brazil due to the potential of range recovery and maintenance. After labeling of these practices as iCL systems, producers switched to a simultaneous rotation that resulted in income diversification (Macedo 2009).

From that, farmers more involved in livestock production, perceive crop integration as a means of strategically maintain pastures and produce cash crops for markets. The same happens for grain farmers who seek economic advantages of diversifying production and improving land use by establishing pasture and animals, for milk, meat and fodder production (Anghinoni et al. 2013).

Integrating forestry activities to iCL models mentioned above results in iCLF systems that consequently generate higher income diversification, which in turn results in a complex set of interactions among all the elements in the production system. In addition, the systems tend to fulfill requirements of environmental compliance provided by the Brazilian Forest Code (Balbino et al. 2012).

Even with an increased effort to boost the adoption of IAPS, it is still happening at a low rate (Balbino et al. 2011). As a result of a survey regarding adoption of the four models mentioned above, Gil et al. (2015) provide the ranked reasons of adoption in Mato Grosso (Figure 6.5).

Note: Adapted from (Gil et al. 2015).

Figure 6.5 *Ranking the most to least attractive criterion to adopt IS in the State of Mato Grosso*

As shown in Figure 6.5, farmers ranked the "potential of higher income" as the most attractive reason for adopting IAPS while "improvement of environmental conditions in the farm as a whole" was the least attractive. With that, a possible strategy to improve the adoption of IAPS in Brazil is promoting their economic benefits, as well as offering subsidies or other financial incentives producers for adopting them.

6.3. Low Carbon Agriculture (ABC Program)

The 15th Conference of the Parties (COP-15), held in December 2009 in Denmark, set up negotiations for the joint reduction of greenhouse gasses (GHG) emission and climate change in the short and long-term (United Nations Framework Convention on Climate Change 2009).

Brazil was one of the signatory countries promising to reduce GHG emissions by 36.1% to 38.9% by 2020, an estimation of 1 billion tons of carbon dioxide equivalent (Balbino et al. 2012; Ministério do Meio Ambiente 2015). From that, a section for reducing GHG emissions in agriculture and other production sectors was added in the Federal Law n° 12.187/2009 (Ministério do Meio Ambiente 2015).

ABC-Plan was, then, created to be the foremost strategy to stimulate low carbon emission agricultural practices and meet the goal for the agricultural sector (Ministério do Meio

Ambiente 2015). Due to the recognized potential of reduced GHG emissions (Balbino et al. 2011), the implementation of integrated crop-livestock-forestry systems, represent one of the six activities included in the ABC-Plan targeting an increase of 4 million hectares by 2020, which accounts for 18 to 22 million tons of carbon dioxide equivalent (Ministério da Agricultura, Pecuária e Abastecimento 2012).

To achieve this, the Brazilian government offers credit lines with reduced interest rates and several terms of payment, according to the financial conditions of producers as well as the quality of the project presented for requesting the loan (Banco Nacional de Desenvolvimento Econômico e Social 2015b).

From that, producers are requested to present to the bank a general plan of production that meets the ABC requirements for low carbon emissions in agriculture (Banco Nacional de Desenvolvimento Econômico e Social 2015b). There are several banks enrolled in the program, which enables the accessibility to the program in the national territory.

6.4. Results

By assessing several experiments on IAPS in Brazil, the present paper compiles qualitative and quantitative information about integrated models to assess the level of benefits and limitations integrated systems present within the national territory.

The first step of the data compilation refers to the findings of Table 6.1, which shows the advantages and disadvantages of IAPS based on economic, environmental and social criteria.

Table 6.1 *Advantages and disadvantages of integrated agricultural production systems.*

Area	*Advantages*	*Disadvantages*
Environmental	Interruption pest cycle [1],[5],[6],[8],[10] Lower env. Pressure [1],[10] Pasture & soil resources recovery [2], [3],[6],[8],[7] Reduced soil degradation [2] Reduced soil compaction [2],[9] Higher organic matter [2],[3][8],[10] Carbon sequestration [2],[3],[4],[8],[10] Increase soil fertility [3],[8],[9] Prevent deforestation [3] Ecosystem services [3],[4] Weed control [5],[10] Improve livestock performance [8]	Soil compaction due to cattle treading [6][10]
Social	Creation of cooperatives [1] Better rural conditions [1],[4],[10] Job creation [2],[4] higher food supply [10] Food security [4]	Information Asymmetry [3] Higher labor expertise Use of different machinery Few research
Economic	Income diversification [1],[6],[7] Higher machinery efficiency [1],[4] Higher labor efficiency [1],[4] Lower production costs [2], [4],[7] Higher farm income [2],[6],[10] Less use of agrochemicals [2],[4],[8],[7],[10] Higher yield [2],[4],[5],[8],[9] Efficient input management [6],[8]	Lowe yield due to shade of trees [3] Costs land use conversion [3]

From that, the second step of data management refers to the outcome of Table 6.2, which depicts the quantitative measurement of the positive or negative impacts of integrated agricultural production systems.

***Table 6.2** Magnitude of IAPS impacts*

System	Criterion	Magnitude	Reference
iCL	Animal performance	8,8%-28% higher animal weight	[10]
		20% weight gain in low land conditions	[10]
		582.0 (kg ha−1)	[8]
		3 times higher animal stock	[10]
		38 - 50% less time to slaughter	[13]
		54% higher birth rates	[13]
		50% less heifer mortality	[13]
		36% less farrowing interval	[13]
	Crop Yield	Additional 6 bushels of soybean ha−1	[10]
		41% reduction fodder (B. decumbens)	[10]
		24% increase rice productivity – RS	[10]
		10% higher yield for maize	[12]
		127kg/soybean/year of pasture	[10]
		18% gain soybean without additional fert.	[11]
	Soil traits	Org. matter loss: Conv. 540kg/ha; iCL 80kg/ha	[10]
		soy/pasture 30% more org. matter	[10]
	Cost	39% less costly live weight-1	[10]
		Positive energy balance of 3,9 J21:M30GJ	[10]
iLF	Soil traits	increase 1.2% organic matter first layer	[10]
iCLF	Crop Yield	41% reduction fodder (B. decumbens)	[10]
		44% reduction nutritional value (B. decumbens)	[10]

6.5. Discussion

The scientific literature highlights the contribution of IAPS on environmental, social and economic levels. Despite variations in terminologies and element arrangement, they basically represent the same system (Carvalho et al. 2014). Nevertheless, complexity and synergism change accordingly with the amount of integrated activities.

The four major categories of IAPS assessed in this paper potentially trigger advantages and limitations for adopters. The positive aspects shown in Table 6.1 are often intertwined, leading to gains to the farm, the environment, and to business profitability. More economic stability leads to a series of social benefits to the household or even to a macro level.

Prior to the analysis of impacts, it is key to understand that farmers differ in a series of characteristics and, therefore, the adoption of productive systems should be done accordingly. This way, models of integration potentially adapt to the farm characteristics and generate benefits for farmers.

To illustrate the impacts of IAPS we take an example of a cattleman. The foremost activity is the production of grass as animal feed and, consequently, live animals. The ongoing production of grass, often *Brachiaria decumbens*, in conjunction with animal activity on the soil, trigger losses in productivity of animals and grass, due to soil compaction and nutrient losses.

In this situation, the adoption of iCL would enable rotation of crop and the well-established livestock activity in the farm. As shown in Table 1, the potential impact would be the recovery of soil and pasture, reduced soil degradation, increased soil fertility, prevention of deforestation of additional areas as increased grazing land as well as income diversification. Rotation with soybean, for instance, promotes biological fixation of nitrogen, which in turn, reduces the demand for fertilizers.

From Table 6.2 it is possible to observe the magnitude of the benefits of IAPS. Integrating crop and livestock activities improve nutritional levels of forage, which enables better animal performance at different levels. Animal weight increases by 28%, potential for animal stock triples, the mortality rate decreases 50%, and the birth rate increases by 54%. All these factors potentially reduce production cost by 39%.

Farmers who predominantly produce soybean, maize, rice, and cotton, also have livestock integration as an option for income diversification and for improving farm environmental conditions. Differently from monocropping systems, integrating livestock interrupts insect and disease cycles and promotes weed control. This way, agrochemical application reduces, leading to lower input costs. Roots of *Brachiaria decumbens* explore deeper layers of soil, which improves soil aggregation.

As shown in Table 6.2, due to iCL, experiments found an increase in crop yield by 10% for maize, 24% for rice and 6 additional bushels of soybean per hectare. Fertility from crops and grass rotation resulted in 18% increase of soybean yield without demanding additional fertilizers.

When producing under no-tillage systems, the use of fewer mechanical operations reduces soil compaction, improve water infiltration, and increase organic matter and carbon stock in the soil. The synergism among systems enhances the physical and chemical characteristics of the soil, leading to higher animal and plant production. From Table 6.2, organic matter losses can be as high as 540 kilograms per hectare in conventional systems, while in iCL the losses are reduced to 80 kilograms per hectare.

The adoption of forestry activities in farms of livestock and crops improves the process of carbon sequestration; the shade of the trees is proven to be beneficial for animal performance since animals tend to graze and ruminate more under the trees. It also accounts for higher income diversification by enabling the production of timber and non-timber goods.

By adopting IAPS producers can adjust production accordingly to market characteristics. In other words, income diversification reduces the risks of businesses since it does not rely on one single product; rather, producers are able to supply different outputs to the market and focus on those with higher value. Moreover, due to production diversification, in case of natural hazards such as hail, flooding, and droughts, IAPS potentially reduce the risks of economic losses.

Social benefits are related to the higher economic potential of IAPS. From the scientific literature, IAPS stimulate job generation, improve rural conditions for living and producing, and guarantee food security. Within this frame, IAPS stimulated the creation of small cooperatives in different rural areas in Brazil due to higher food surplus. Therefore, this represents a cyclical process where producers reap continuous economic and social benefits.

Nevertheless, Brazilian producers lack key information on how implementing IAPS, leading to misgiving and fear towards adoption. Although it has not been scientifically proven, many producers believe that cattle treading triggers soil compaction and affects production. IAPS is more complex than conventional agriculture, as they require higher labor expertise to define the suitable amount of inputs, animal stock, trees arrangement to promote less costly mechanical operations and market “know-how”.

Although IAPS are applicable for any farm size and region (Balbino et al. 2012), to adopt different integration models, it is necessary to adapt machinery, labor, and farm structure accordingly to the production system (Macedo 2009).

Integrating forestry demands strategic tree arrangement since tree shades may block the sunlight for crops, leading to lower productivity. In this sense, when compared to multiple rows of trees, single rows are expected to be more beneficial for enabling light incidence on crops and pasture. Table 6.2 shows that shade affected fodder production by 41% and nutritional value by 44% in *Brachiaria decumbens*. In contrast, another experiment shows that already in the first year, soil organic matter increased by 1.2% due to the presence of trees.

In addition, converting land use from mono-cropping to integrated models is costly and requires strategic planning. As a result, small and big producers need governmental support to stimulate the adoption of IAPS, however, programs such as the ABC-plan have shown considerable bureaucracy to offer financial means for potential adopters.

Despite the effort to meet the goals of the program, there are hindrances to access credit lines (Ministério da Agricultura, Pecuária e Abastecimento 2012). In the State of Pará, which presents the second highest level of pasture degradation in the Legal-Amazon area, producers evaluated the program positively insofar as loan conditions are attractive to implement IAPS and pasture recovery. Nevertheless, land ownership is an issue in the Amazon, as the federal government lacks efforts towards legal land regularization, and land distribution, which hampers possibilities for developing sustainable agriculture in the region (Ministério da Agricultura, Pecuária e Abastecimento 2012).

On the other hand, those who succeeded claim that the credit amount is insufficient to implement IAPS and maintain them (Ministério da Agricultura, Pecuária e Abastecimento 2012). The ABC-Plan enables farmers to request credits only once, therefore those who implemented IAPS, for instance, are not eligible for additional governmental support for maintaining the new system (Ministério da Agricultura, Pecuária e Abastecimento 2012).

Another challenge stands for the lack of environmental regulation for the majority of producers interviewed. They state a significant absence of technical assistance and advisory services in the Amazon region. A feasible solution, therefore, could be the creation of a credit line for hiring these services (Ministério da Agricultura, Pecuária e Abastecimento 2012).

As for the state of Mato Grosso, the survey from (Gil et al. 2015) shows that only 17% of the farmers interviewed applied for a credit line, but even fewer (5.9%) succeeded. Producers reported that bureaucracy was the major challenge for the application. Although the ABC credit lines were attractive even for producers with enough own capital, they opted for not requesting the loans due to the number of required documents as well as the need to comply with environmental laws.

It suggests that for the ABC-plan to succeed, additional government efforts toward environmental awareness are needed. Legal regulation and redistribution of land ownership, provision of advisory services to small and big producers, improving information symmetry as well as enforcing environmental regulation according to the Brazilian Forestry Code are key elements to trigger higher adoption of IAPS.

The literature also states the lack of scientific experiments about the benefits and improvements of integrated models. It is especially because results rely on long-term experiments, demanding high costs and ongoing labor.

Chapter 7. Can preferential credit programs speed up the adoption of low-carbon agricultural systems in Mato Grosso, Brazil? Results from bioeconomic microsimulation

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This chapter has been published[9] in Regional Environmental Change in January, 2017.

Abstract

The need to balance agricultural production and environmental protection shifted the focus of Brazilian land-use policy towards sustainable agriculture. In 2010, Brazil established preferential credit lines to finance investments into low-carbon integrated agricultural systems of crop, livestock, and forestry. This article presents a simulation-based empirical assessment of integrated system adoption in the state of Mato Grosso, where highly mechanized soybean-cotton and soybean-maize double-crop systems currently prevail. We employ bioeconomic modeling to explicitly capture the heterogeneity of farm-level costs and benefits of adoption. By parameterizing and validating our simulations with both empirical and experimental data, we evaluate the effectiveness of the ABC Integration Credit through indicators such as land-use change, adoption rates and budgetary costs of credit provision. Alternative scenarios reveal that specific credit conditions might speed up the diffusion of low-carbon agricultural systems in Mato Grosso.

7.1. Introduction

The Federal Government of Brazil is aware of its great responsibility to combat climate change. During the 15th Conference of the Parties (COP15) of the United Nations Framework

[9] Carauta, M., Latynskiy, E., Mössinger, J., Gil, J.D.B., Libera, A., Hampf, A., Monteiro, L., Siebold, M., Berger, T., 2017. Can preferential credit programs speed up the adoption of low-carbon agricultural systems in Mato Grosso, Brazil?: Results from bioeconomic microsimulation. Regional Environmental Change 27, 675. 10.1007/s10113-017-1104-x.

Convention on Climate Change (UNFCCC), the government pledged to take domestic actions to substantially decrease its greenhouse gas (GHG) emissions. According to this pledge, national greenhouse gas emissions shall be reduced by 36.1–38.9% until 2020. As a consequence, a major mitigation effort must be made in agriculture and land use, which currently account for more than 60% of Brazil's annual GHG emissions (Ministry of Science, Technology and Innovation 2016). Agriculture alone is expected to reduce 166 million tons of CO_2eq (or 43%) of the national mitigation efforts by 2020 (World Bank 2010, 2011; Mozzer 2012). However, this should not undermine the sector`s great economic and political importance, earning around 52% of the total national exports.

Brazil aims to simultaneously ensure climate change mitigation and economic development by offering farmers incentives to switch to low-carbon agricultural practices. A special credit program has been launched in 2010 as part of the Federal Government's Strategy for Low-Carbon Agriculture ("ABC Plan" from Portuguese "Agricultura de Baixo Carbono"). The program supports the adoption of integrated crop-livestock-forestry systems by providing preferential loans to their adopters. Still, the impacts of this program remain largely unclear as comprehensive empirical data are lacking concerning (1) the current inventory of integrated systems and (2) the effective use of ABC *Integration* credit at farm level. Evaluations of the ABC credit program have been made recently but only through supply-side analyses of borrowed amounts (Observatório ABC 2015). Other studies conduct cost analyses based on data from a single farm (Oliveira Silva et al. 2015) or investment analyses of single production alternatives (Bezerra et al. 2011; Federação da Agricultura e Pecuária do Estado de Mato Grosso 2013). Gil et al. (2015) present an overview of integrated land-use systems in Mato Grosso and investigate the determinants of their adoption. According to Gil et al. (2016), from the farmer perspective, there is evidently a high degree of uncertainty regarding the synergy effects of integrated systems as well as their economic performance.

Against this background, the present article is the first to assess the ABC Integration program through a "holistic" demand-side approach based on a quantitative assessment of farm systems in the state of Mato Grosso. Our study considers farmer economic incentives as well as the heterogeneity of local farm holdings in terms of resource endowments, investment opportunities, as well as environmental, technical and market conditions. For our policy assessment, we apply *bioeconomic microsimulation*, combining the software packages MPMAS and MONICA. The model set-up, parameterization, and validation are described in the following sections. Through computer simulations we evaluate the policy potential of current and alternative ABC credit lines in Mato Grosso and offer suggestions for their implementation. Our simulation results thereby provide detailed information on the effectiveness and efficiency of the ABC Credit Program in supporting specifically the adoption of integrated land-use systems.

7.2. Study Area

7.2.1. Agro-ecological conditions

Mato Grosso is the third largest state of Brazil extending over 903,000 km^2 (Brazilian Institute of Geography and Statistics 2015), which amounts to the area of France and Germany combined. Since the 1970's, Mato Grosso experienced a rapid expansion of agricultural and pasture lands coupled with deforestation of large rainforest and savanna areas (DeFries et al. 2013). Between 1990 and 2013, the area allocated to crop production increased fivefold by 10 million hectares (Brazilian Institute of Geography and Statistics 2016b) with a historical peak in 2004, when annual deforestation reached 11,800 sq. km. (Instituto Nacional de Pesquisas Espaciais 2015). While overall deforestation has significantly decreased since then, recent forest clearance seems to be on the rise again (Fearnside 2015) and land clearing and subsequent soil tillage continue to cause large amounts of GHG emissions (Galford et al. 2011). Favorable climatic conditions allowing for two growing seasons per year, together with the introduction of improved seeds and techniques for dealing with soil acidity, transformed Mato Grosso into a major player in soybean, maize and cotton production (World Bank 2009). In 2013, the state accounted for 29% of the national soybean production, 25% of the national maize production and 52% of the national cotton production (Brazilian Institute of Geography and Statistics 2018). Cattle ranching is another prominent activity in the state, which concentrates 13% of the national cattle herd (Brazilian Institute of Geography and Statistics 2016b).

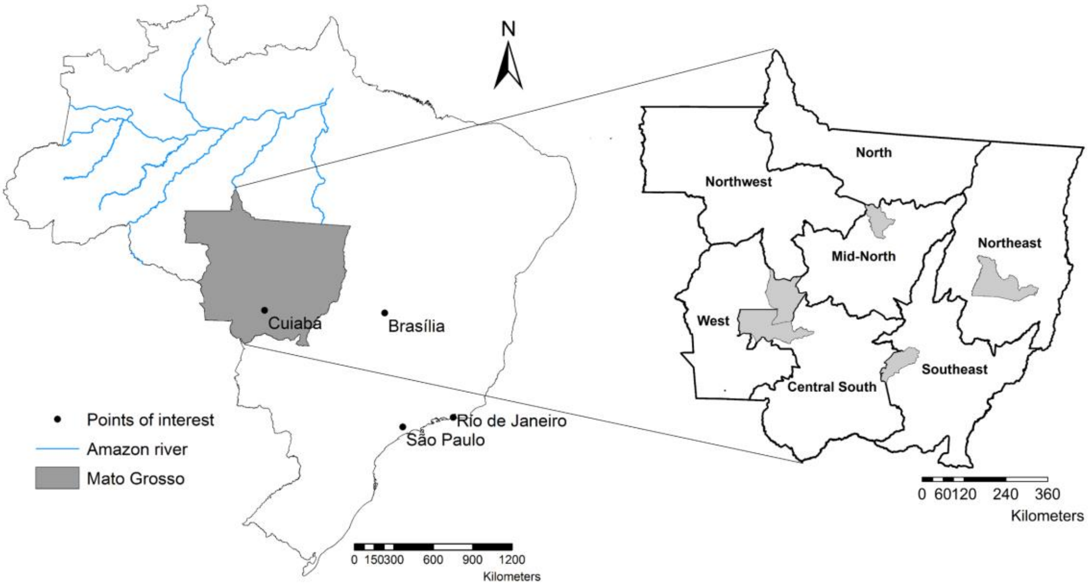

Figure 7.1 *Study area and specific sites used for modeling: the state of Mato Grosso in the west-central region of Brazil (left) and the IMEA study sites (right)*

Mato Grosso's agricultural output is almost exclusively produced in five of the seven macro-regions defined by the Mato Grosso Institute of Agricultural Economics (Instituto Mato-Grossense de Economia Agropecuária 2010b). In each of these five macro-regions, IMEA selected one representative survey site (gray shaded areas in the right pane of Figure 7.1), which taken together provide the data basis for our policy simulation analysis in this paper.

7.3. Policy setting

As mentioned above, the ABC Plan is one pillar of Brazil's strategy for GHG mitigation. It seeks to stimulate the adoption of low-carbon agricultural practices through its dedicated credit programs (herein "ABC credit"). The program offers preferential loans to farmers for implementing one or several of the following agricultural practices: (i) integrated systems of crops, livestock and forestry, (ii) restoration of degraded pastures, (iii) no-tillage farming, (iv) biological nitrogen fixation, (v) treatment of animal waste, and (vi) commercial forestry plantations (Ministério da Agricultura, Pecuária e Abastecimento 2012).

In our present study, we focus exclusively on the credit line ABC Integration for integrated systems of crops, livestock and forestry (Banco Nacional de Desenvolvimento Econômico e

Social 2015b). There are several motivations to support these land-use systems that are up to now relatively new in Mato Grosso: (i) tree plantations as part of an integrated system increase wood and energy supply, potentially reducing pressure on natural forest areas (Federação da Agricultura e Pecuária do Estado de Mato Grosso 2013); (ii) tree plantations contribute to carbon sequestration; (iii) integration of crops and livestock may increase returns per hectare and, therefore, spare land (Strassburg et al. 2014; Cohn et al. 2014); and (iv) the interaction between crops, livestock and trees may increase crop yield and livestock output (Assmann et al. 2003).

At the time of our analysis, subsidized credit of ABC Integration had an annual interest rate of 5% (Banco Nacional de Desenvolvimento Econômico e Social 2015a), which is a very lucrative opportunity, considering that the annual interest rate of the Brazilian Central Bank is around 12% (Banco Central do Brasil 2015). The official documentation (Banco Nacional de Desenvolvimento Econômico e Social 2015b), however, lacks a clear definition of what exactly is considered as a tree plantation in integrated systems. According to our discussions with local experts, the common practice is to use a lower bound of forest area of 10%. This means that a livestock-forestry system, for example, with ten hectares, should have at least 1 hectare of forestry integrated with livestock production. In integrated systems with cattle, the frequency of crop rotation differs but the land is usually used for grazing at least once every four years in all systems (Gil et al. 2015). Like in the case of systems with forestry, for systems with cattle the criterion is also quite imprecise. The final verdict is made by local bank managers from accredited financial organizations, who decide whether the farmer application is eligible for preferential credit.

7.4. Methods and Data

7.4.1. Methods Used

For our assessment of low-carbon land-use options and the impacts of policy interventions, we apply bioeconomic microsimulation (Troost et al. 2015; Troost and Berger 2015). Bioeconomic microsimulation refers to farm-level modeling of all farm holdings in a specific study area to capture policy response subjected to farm heterogeneity. We simulate the decision-making of each farm holding over time using whole-farm mathematical programming integrated with a regionalized crop-growth simulation model. In our study, we have not yet simulated interactions between farm holdings, for example, in land markets or information communication networks. This makes our present bioeconomic micro-modeling approach a disconnected multi-agent system, following the definition of Berger et al. (2006). Work is ongoing to parameterize also farm agent interactions in our bioeconomic modeling approach, which would then yield a fully connected multi-agent system.

Our bioeconomic microsimulation was implemented using MPMAS, a multi-agent software package developed for simulating farm-based economic behavior and human-environment interactions in agriculture (Schreinemachers and Berger 2011). This software has been applied in a number of empirical studies focusing on innovation diffusion in agriculture berg (Berger 2001; Schreinemachers et al. 2009; Schreinemachers et al. 2010; Marohn et al. 2013; Quang et al. 2014) as well as for integrated assessment of farm-level agricultural policies (Berger et al. 2006; Troost et al. 2015; Wossen and Berger 2015). Software architecture and model equations of MPMAS are described in greater detail in (Schreinemachers and Berger 2011), following the ODD-protocol.

Our MPMAS application was combined with the process-based biophysical simulator MONICA (Nendel et al. 2011). This model integration is extremely important for our study purpose since it allows us to capture local environmental conditions and constraints in our mathematical programming approach and, thus, incorporate them into farmers' decision making. MONICA is responsible for simulating crop yields for various crop maturity groups, fertilizer application levels, soil types and climatic conditions. Further details about our MPMAS_MONICA integration can be found in Carauta et al. (2016a) and Carauta et al. (2016b). MONICA has been specifically parameterized and calibrated for the study area using 2000-2013 weather data. Simulated crop yields for all soybean, cotton and maize production alternatives implemented in MPMAS have been stored on a MySQL server. We set up a specific database application (called "mpmasql"), which accesses the database and converts the stored parameters into model input for MPMAS. For simulating agent decisions (see details below), MPMAS uses COIN's CBC mixed-integer programming solver, which we fine-tuned for this study. The MPMAS software, R scripts, input and output files, and model documentation can be downloaded from "http://www.uni-hohenheim.de/mas/software/BrazilSupplement.7z".

7.4.2. Input Data and Model Parameterization

As shown in Figure 7.1, we parameterized MPMAS_MONICA for the five survey sites of IMEA in Mato Grosso: Canarana (Northeast), Campo Verde (Southeast), Sapezal (West), Sorriso (Mid-North), and Tangará da Serra (South Central). Crop production requirements for bioeconomic modeling were estimated using production cost surveys of Instituto Mato-Grossense de Economia Agropecuária (2013a) and the crop-level dataset of a Brazilian agricultural consultancy company (Céleres 2013). Costs of inputs, transportation, and processing, as well as conditions of credit and taxes refer to the harvest season 2013/2014 and were also taken from Instituto Mato-Grossense de Economia Agropecuária (2013a). Site-specific time-series of prices for agricultural products were obtained from the online price database of Instituto Mato-Grossense de Economia Agropecuária (2015). Purchase prices for agricultural machinery were compiled from local traders, while operational costs of machinery were estimated using the methodology of the Brazilian National Supply Company (Brazilian National Supply Company 2010). Information on soils was taken from the geo-referenced soil database of Brazil (Muniz et al. 2011) and from official socio-ecological zoning maps produced by the Mato Grosso State Secretary of Planning (Secretaria de Estado de Planejamento e Coordenação Geral de Mato Grosso 2011).

The agent population in MPMAS_MONICA includes all crop-producing farm holdings in the five IMEA sites that operate on more than 50 hectares according to the latest agricultural census available (Brazilian Institute of Geography and Statistics 2006). At the time of the census, these 844 farm holdings constituted 99% of all crop-producing farms in the IMEA sites in terms of agricultural area and 74% in terms of number. Using the empirical data from the Brazilian Agricultural Census (Brazilian Institute of Geography and Statistics 2006) and from the IMEA agricultural survey (Instituto Mato-Grossense de Economia Agropecuária 2013a), we created a statistically consistent population of 844 model agents following the Monte Carlo approach of Berger and Schreinemachers (2006).

Regarding agent decision-making, we implemented a recursive whole-farm planning approach based on mathematical programming as described in Schreinemachers and Berger (2011). Each model agent seeks to maximize the expected farm income subject to its individual land, labor and cash endowments, as well as specific crop rotational and farm technical constraints. It is important to note that agents in MPMAS will only select production alternatives that are profitable to them. This microeconomic foundation makes MPMAS simulation results highly realistic as real-world farmers typically avoid unprofitable production alternatives or quickly abandon them in case they have taken them up based on too optimistic expectations (Berger and Troost 2014).

In every simulation period of MPMAS, which corresponds to one real-world agricultural year, agents actually take 3 decisions: an investment decision, a production decision, and a consumption decision. During the investment decision stage, each agent decides in which durable assets (e.g. machinery, livestock, tree plantations) to invest. The agent investment decision is taken based on the values of farm resource requirements, prices and yields expected in the long-run. Agents can purchase assets both on loan and with full self-financing. At this stage, agents may also decide to apply for ABC Integration credit in order to invest into low-carbon integrated systems complying with the official regulations released by the Brazilian Development Bank (Banco Nacional de Desenvolvimento Econômico e Social 2015b).

In the subsequent production decision stage, model agents set up the farm operational plan for the current period and select the specific seeds and breeds as well as fertilizer and feed application rates for soybean, cotton, maize, eucalyptus, teak and cattle production. The agent production decision is based on individual resource requirements, prices and yields expected for that period, adding possible new assets purchased as part of the agent investment decision.

For the agent consumption decision stage, MPMAS simulates the individual economic performance (e.g. cash flow, savings, withdrawals, payback of credit tec.) of each model agent based on actual prices and crop yields (simulated in MONICA), and updates the agent’s liquid and physical assets and liabilities. The resulting values for each agent are finally carried over to the next simulation period and form the initial values for the subsequent investment and production decisions. One agent optimization problem contains up to 3,819 decision variables (including 150 integer variables) and 3,887 constraints.

7.4.3. Implementation of Integrated Production Systems

Integrated production systems in MPMAS are implemented as combinations of crops, livestock, and trees on the same farm plot. Unfortunately, long-term experimental results on possible interaction effects between system components are not yet available for integrated systems containing tree crops in Mato Grosso. In the case of crop-livestock interactions, short-term experiments have already been conducted in conditions similar to those of our study area (Landers 2007; Flores et al. 2007; Silva et al. 2012; Kunrath et al. 2015) and suggest that the magnitude of short-term profitability effects is rather small. Given such limited evidence, we opted for not including any interaction effects in our present model implementation.

Four types of low-carbon systems with tree crops have been implemented in MPMAS: three with eucalyptus (*Eucalyptus urograndis*) and one with teak (*Tectona grandis*). The first eucalyptus system is for charcoal production and has a 7-year production cycle. The second eucalyptus system focuses on charcoal and wood production and has a 12-year production cycle. Model parameters for both of these systems (including investment costs, labor, and machinery requirements as well as charcoal output) were estimated from Federação da Agricultura e Pecuária do Estado de Mato Grosso (2013). The third system is a wood-only eucalyptus seedling and coppicing double-planting system that has a 14-year production cycle based on Rode et al. (2014). Finally, for teak, we implemented a novel production system with a 20-year production cycle, as described in Bezerra et al. (2011). We estimated the model prices for forestry products from the online database of the Department of Agriculture and Supply of the Parana State (Secretaria da Agricultura e Abastecimento do Paraná 2015). The risk premium for discounting future values of forest investments in our analysis was set to 4.9%, which is the value commonly chosen for agricultural investment analysis by local banks.

For the implementation of cattle production alternatives, we used data on livestock systems from Anuário da Pecuária Brasileira (2013). In total, our model agents can select among nine cattle production systems with different intensity levels (extensive, semi-intensive or intensive) and production cycles (breeding, fattening or full cycle). Agents can practice each of the nine systems either with brachiaria grassland pasture (*Brachiaria brizanta*) or unmanaged grazing land. The carrying capacities of both pasture types and the costs of brachiaria pasture formation were also taken from Anuário da Pecuária Brasileira (2013).

7.5. Model Validation and Simulation Experiments

7.5.1. Model Validation

Empirical validation of bioeconomic microsimulation models is commonly done by comparing the model output (endogenous variables) with the corresponding observed values (Fagiolo et al. 2007). Our model validation followed the methods described in Troost and Berger (2015), Carauta et al. (2016a) and Carauta et al. (2016b). For the validation of the MPMAS application presented here, we used two benchmarks: modal single farm land-use data of Instituto Mato-Grossense de Economia Agropecuária (2013a) for farm-type validation and municipality land-use data of Brazilian Institute of Geography and Statistics (2018) for municipality-level validation. Conducting two separate validation tests at two levels of aggregation is necessary given that our agent-based model component simulates both the behavior of individual farms and the agricultural land-use patterns of the study area as a whole.

For the farm-type validation, we inserted the farm profiles (i.e. information on land ownership, asset endowments, and location characteristics) specified by Instituto Mato-Grossense de Economia Agropecuária (2013a) as model input and run MPMAS to simulate the land use of these farm agents. Then, we compared the simulated agent land use (by crop and season) with the land use recorded by IMEA and calculated a model efficiency based on standardized absolute errors (ESAE) of 0.47, which in our opinion is sufficient for this first policy analysis study. Troost and Berger (2015), for example, report values for ESAE at farm-type level between 0.62 and 0.71 but had detailed farm survey data available for their model parameterization. We are therefore confident being able to achieve similar model efficiency once the new IMEA dataset of 2016 becomes accessible to us. For the municipality-level validation, we compared the simulated and observed land-use shares of soybean and maize in total cropland by each municipality. At this level, ESAE model efficiency reaches 0.92.

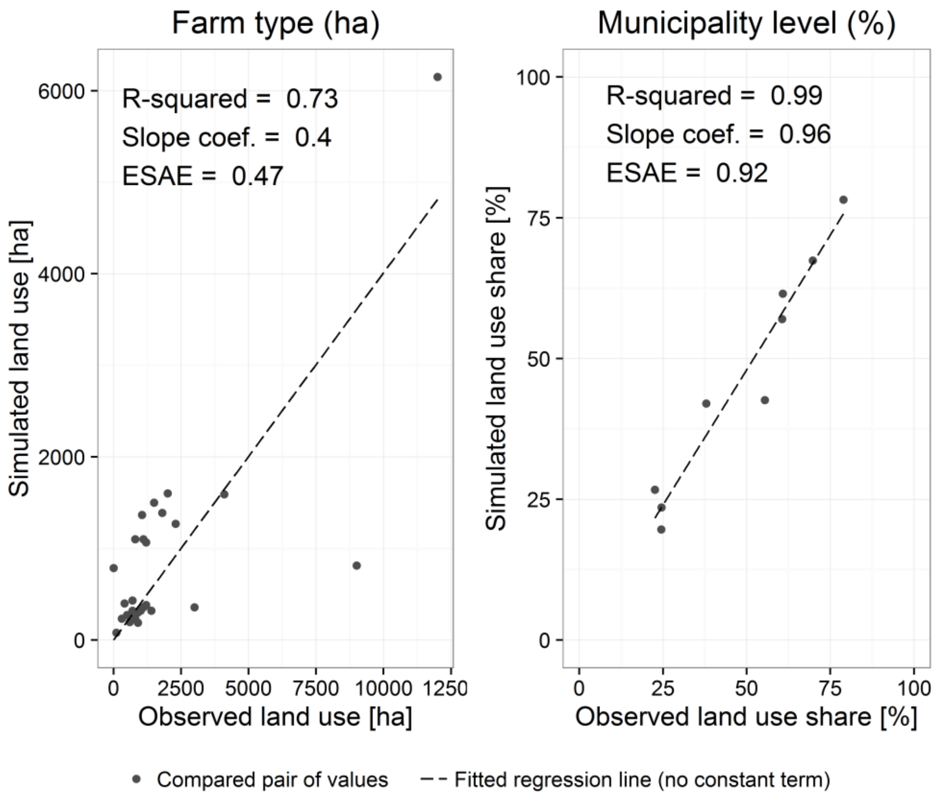

Figure 7.2 *Validation of agent-based model component*

Figure 7.2 depicts scatter plots of observed and simulated land-uses for both validation tests to visualize the goodness of model fit at disaggregate and aggregate level. The fitted no-constant regression lines (slopes close to unity) and their calculated R-squared (0.86 for the farm types and 0.99 for the municipality level) indicate a good model fit. The slope coefficient of the regression lines for the farm-type level reaches a value of 0.81, which means that the model underestimates the areas of cropland by 19% on average. The slope coefficient of 0.96 for the municipality level indicates that the model underestimates the land-use shares of soybean and maize by 4% on average, which stems from slightly overestimating the land-use share of cotton. As already mentioned above, we could not obtain empirical data concerning the adoption of low-carbon integrated systems specifically in our study areas. Therefore, simulated values of integrated systems land use were cross-checked by local experts and judged against observed values found by Gil et al. (2015).

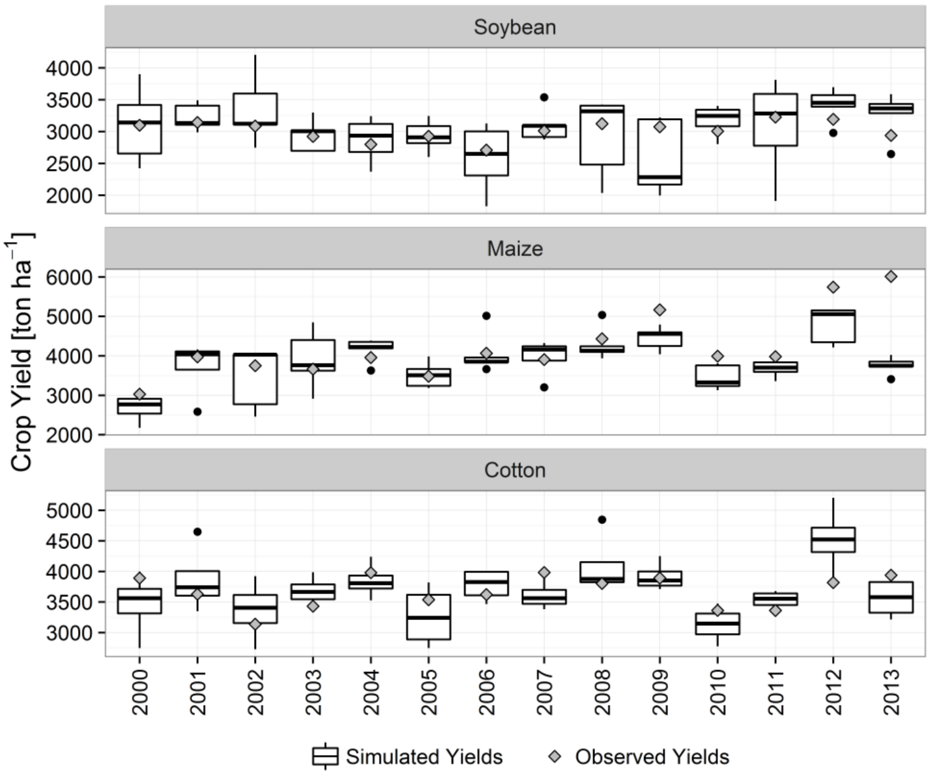

Figure 7.3 *Validation of soil-crop model component*

The MONICA application was validated at the municipality level, by comparing simulated yields to observed crop yields of each municipality and crop season between 2000 and 2013 (Brazilian Institute of Geography and Statistics 2016a). A validation at the farm-level was not possible since crop management and yield data were not available for individual farms. Figure 7.3 compares the simulated crop yields of soybean, maize, and cotton with the ones observed by IBGE. In most of years, the empirical average lies well within the range of yields simulated with MONICA.

In general, the results of our empirical validation suggest that a very good match at municipality level was achieved, whereas the farm-type level response was less well matched. The latter is a common problem in farm-level models owing to the lack of data and the inherent unpredictability of individual human behavior which, as is the case here, might average out at more aggregate levels. Still, we believe that this does not affect the robustness of the conclusions we derive from our policy analysis.

7.5.2. Simulation experiments

Having validated the MPMAS and MONICA model components, three simulation experiments were considered for our policy impact assessment:

Experiment #1 ("ABC adoption") assesses the adoption impact of the ABC Program by comparing a baseline scenario [ABC] reflecting the ideal situation, in which all model agents have access to ABC Integration Credit (but may not take it), with a counterfactual scenario [NO_ABC], where no subsidized credit is made available to the model agents.

Experiment #2 ("Alternative financing") tests possible variations in financing conditions of the ABC program for integrated systems. This was done by comparing the baseline scenario [ABC] with the following alternative simulation settings:

- "Less Subsidy" [LESS] decreases the subsidized amount by increasing the credit interest rate by one percent to six percent
- "Own Capital 50%" [OC50] reduces the own capital requirement (i.e. down payment share) for integrated system adoption to 50% from currently 60% and 65%
- "Own Capital 25%" [OC25] reduces the own capital requirement to 25%
- "Maximum Amount" [MAX] increases the maximum amount that model agents can borrow by one million BRL

Experiment #3 ("Teak introduction") evaluates the ABC adoption of integrated systems under a possible introduction of teak markets [TEAK]. According to local experts, this might be a promising marketing activity for Mato Grosso that could produce high-quality wood to be sold at superior prices than current eucalyptus wood.

We would like to emphasize here that the baseline scenario in our present policy analysis does not fully reflect Mato Grosso's current credit uptake and integrated systems adoption. Since inventory data of integrated systems are not (yet) available in Brazil, we had no direct observations to calibrate our agent decisions regarding the uptake of ABC credit for integrated systems. We, therefore, decided to create an ideal baseline for this study without any hindering bureaucratic and social factors as identified by Gil et al. (2015). Consequently, our baseline will certainly overestimate the absolute amount of ABC credit uptake and integrated systems area of Mato Grosso's farmers. Still, 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, are well captured in our simulations.

To isolate the direct effects of policy intervention, all experiments were run for 3 agricultural years with constant average prices and crop yields. In addition, we fixed land ownership of model agents by not allowing for land sales and changes in long-term rental contracts. Still, model agents may temporarily rent in or rent out farm land for the duration of one year. Our simulation experiments thus capture the short-term to mid-term effects of policy intervention undisturbed by price and weather variability and long-term dynamics on land markets.

7.6. Simulation Results

7.6.1. Adoption of credit for low-carbon agriculture

Figure 7.4 shows the simulated impacts of the ABC program for low-carbon agriculture in terms of land-use change. The left and right panels indicate the share of integrated systems in the absence and presence of ABC credit, respectively. While the share of integrated systems in the West macro-region is almost equally high in both situations, agents in other IMEA macro-regions (especially in Mid-North, South Central and Northeast) increase their share of integrated systems considerably. The dotted line in both panels indicates the land-use share of integrated systems averaged over all model agents. Accordingly, our simulations suggest that with ABC credit the adoption of integrated systems more than doubled, reaching an agent land-use share of 27%.

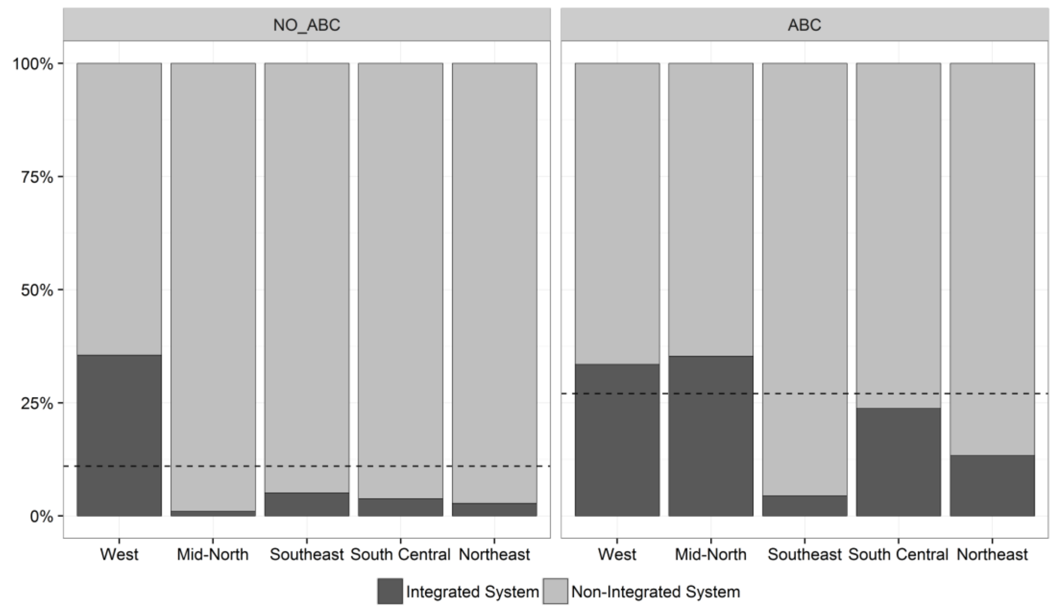

Figure 7.4 *Simulated land-use shares in macro-regions. Scenarios: Baseline (ABC), Counterfactual (NO_ABC)*

Figure 7.5 shows the distribution of integrated system adoption at agent level with and without ABC credit. In our simulations, most agents allocated 1,000 to 2,000 ha of their farmland to integrated systems, with some few large-scale farm agents assigning very large areas to these systems.

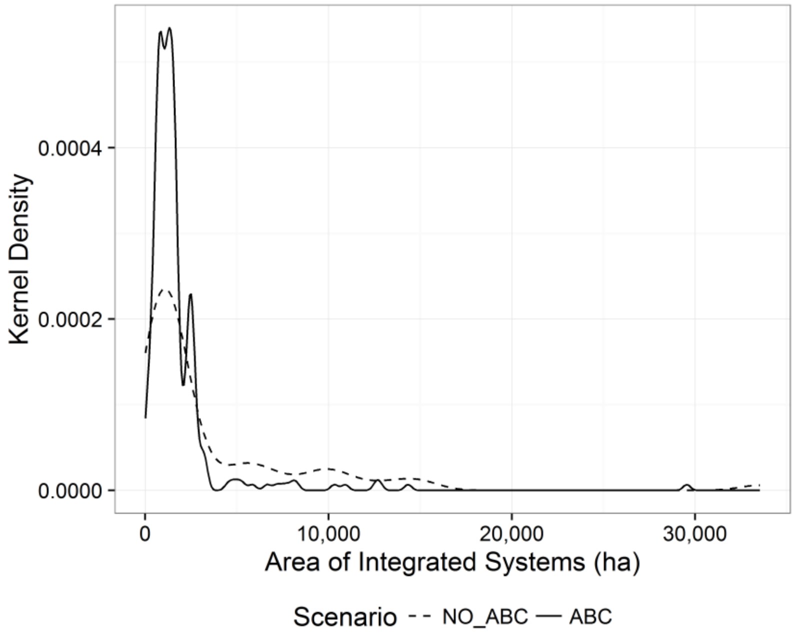

***Figure 7.5** Simulated distribution of Integrated System adoption in macro-regions. Scenarios: Baseline (ABC), Counterfactual (NO_ABC)*

As Figure 7.6 additionally shows, agents in West and Southeast selected predominantly iCL (crop-livestock) systems with ABC credit, while agents in Mid-North, South Central and Northeast preferred iCLF (crop-livestock-forestry). Furthermore, iLF (livestock-forest) systems were not adopted at all, and iCF (crop-forestry) systems were adopted in almost half of the area under integration in the Mid-North and in a quarter in South Central.

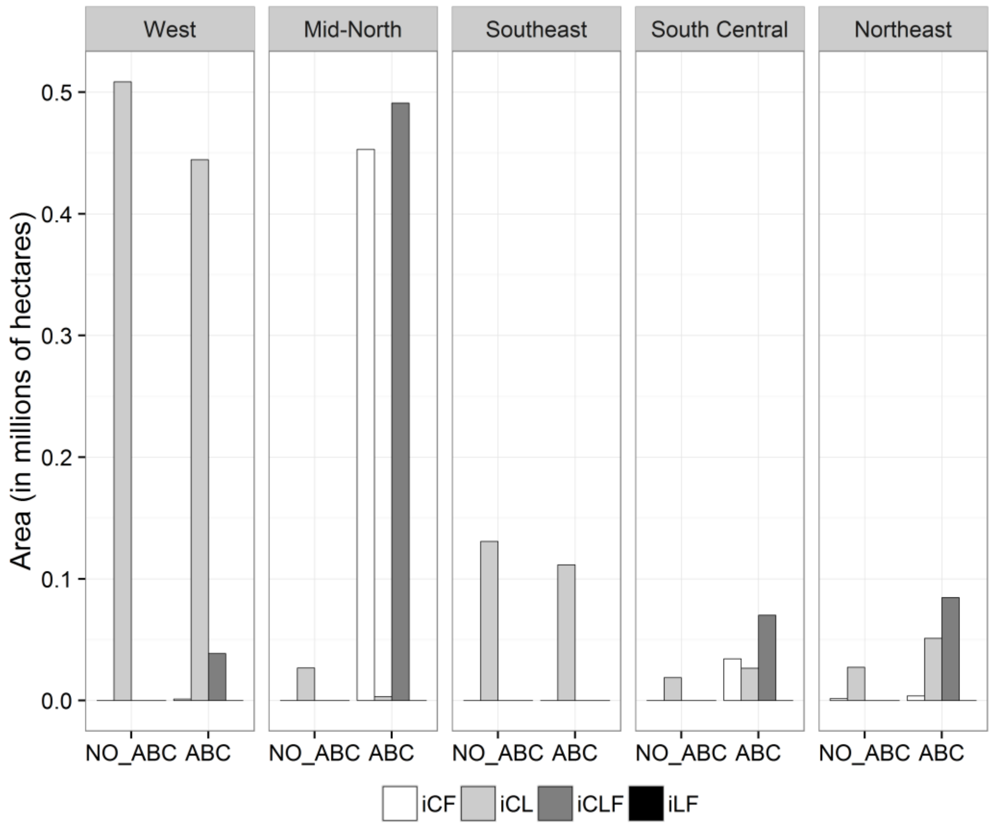

Figure 7.6 *Simulated types of Integrated System adoption in Baseline (ABC) and Counterfactual (NO_ABC) scenarios: crop-forestry system (iCF), crop-livestock system (iCL), crop-livestock-forestry system (iCLF) and livestock-forestry system (iLF)*

7.6.2. Alternative Financing

Figure 7.7 compares the simulated policy costs and land areas for alternative implementations of the ABC Integration Program. The left panel shows the per-hectare policy costs under various financing conditions; the right panel shows the policy costs and their impacts in terms of area, scaled-up to the state level using IBGE sampling weights. Accordingly, providing credit at an increased interest rate (i.e. with less subsidy than under current conditions) was the most cost-effective policy measure, but made agents reduce the total area with integrated systems from 27% [ABC] to 19% [LESS] of all agricultural land. Expanding the upper limit for ABC credit [MAX], led both to an increase of per-hectare policy costs and agent adoption of integrated systems. In contrast, changing the own financing requirements to 50% [OC50] and 25% [OC25] increased the per-hectare policy costs and, at the same time, made agents adopt less area of integrated systems.

After submission of the original manuscript for this article, Brazilian Agricultural Research Corporation (2016) released a survey-based estimate of 1.5 million hectares of integrated systems in Mato Grosso, with crop-livestock systems (iCL) having the largest share of adoption. We note that our up-scaled baseline simulation result of about 1.8 million hectares [ABC] with mainly iCL is in line with this recent estimate.

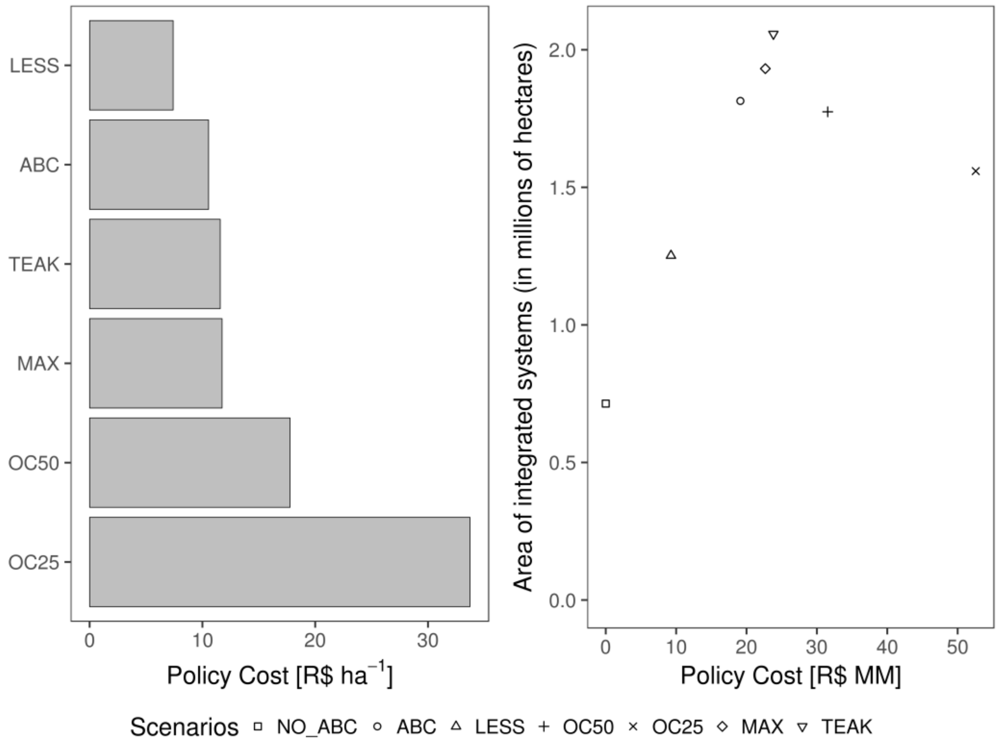

Figure 7.7 *Simulated land use and policy costs upscaled to Mato Grosso, using IBGE sampling weights for land use. Scenarios: Baseline (ABC), (Counterfactual (NO_ABC), Less Subsidy (LESS), Own Capital 50% (OC50), Own Capital 25% (OC25), Maximum Amount (MAX) and Teak Introduction (TEAK)*

7.6.3. Teak Introduction

The assessment of teak as a possible new production alternative is also depicted in Figure 7.7. Accordingly, the introduction of teak amplified the effect of ABC credit in our simulations since it increased the total integrated system area by about 250,000 hectares when compared to the baseline [ABC] scenario. This increase in adoption area was possible in our simulations without excessive increase of policy costs.

7.7. Discussion

7.7.1. Implementation of preferential credit programs

The results of our simulations suggest that ABC credit indeed contributed to the adoption of integrated systems in Mato Grosso. Without preferential credit lines, the adoption of integrated systems would be rather modest at about 11% percent of agricultural land use in Mato Grosso. With the introduction of the ABC program and neglecting bureaucratic and social barriers at farm level, the area of integrated systems probably more than doubled in 2013. Furthermore, in the absence of the ABC Program, almost the entire area of integrated systems would be made up of crop-livestock integration (iCL). With the recent introduction of the ABC Program, our simulations suggest an increase in iCLF (crop-livestock-forestry) and iCF (crop-forestry) systems.

We also found our model agents to be sensitive to changes in financing conditions of ABC credit. Agents with limited liquidity can access various financing sources that differ only slightly in terms of interest rates and upper credit limits. In addition, integrated system adoption yields only slightly higher returns than conventional systems. Small changes in financing can, therefore, trigger larger reallocation of financial resources between competing land uses and credit sources. In our simulations, increasing the maximum ABC amount that agents can borrow [MAX] sped up the adoption of integrated land-use practices. The total area of adoption up-scaled to Mato Grosso state level increased to 28%, while the policy costs per hectare increased to R$47. This finding suggests that especially for large farm holdings (i.e. “thousand hectares plus”) that operate most of the agricultural lands in Mato Grosso, the current credit limits appear to too low.

The most cost-effective scenario in terms of per-hectare policy costs was the scenario [LESS], though in this scenario the overall area of adoption reduces by almost half. This result suggests that the reduction of subsidized credit may lead to subsequent discontinuity of integrated system adoption among many farm holdings in Mato Grosso. In contrast, lowering the own-capital requirements (scenarios [OC50] and [OC25]) for agents when applying for ABC credit, turned out to be a highly cost-ineffective policy measure. Policy costs increased in our simulations considerably, while the area dedicated to integrated systems decreased. This result underlines the importance of farm-level simulation that can capture the liquidity endowment of individual farm holdings and their responses to minor changes in financing conditions. Against these simulation results, the current self-financing share in ABC credit seems appropriate.

In addition, our simulation results suggest that impact and cost-effectiveness of ABC credit vary significantly across our study area. Given the heterogeneity of farming conditions observed in Mato Grosso, it appears ineffective to apply the ABC Program under identical conditions in the entire state. Tailoring financing conditions to smaller geographical units could be achieved, for example, by using IBGE's subdivision of "meso-regions" for location-specific ABC Program implementations.

7.7.2. High-value Timber as an Investment Opportunity

The results of our explorative simulations concerning high-value timber production suggest that enabling more farmers to participate in the teak market could further increase the state's area of planted forests with ABC Integration credit. Once the teak market has been made accessible in our simulations, more model agents adopted forestry systems, increasing the integrated system area in Mato Grosso by about 240,000 hectares. Improving the teak market structure, therefore, appears a promising strategy for future regional development, deserving more attention and research. The improvement could be achieved, for instance, by providing technical support to teak growers through local extension networks, by creating linkages between buyers and producers, or by launching advertisement campaigns of investment opportunities in the teak sector.

7.8. Conclusions

Credit from the ABC Program has not been regarded as a crucial determinant of the adoption of integrated systems in Mato Grosso. In fact, only a small share of current integrated systems adopters have used the ABC credit lines so far (Gil et al. 2015; Observatório ABC 2015). Still, our simulation results suggest that ABC credit substantially increased the integrated system area in Mato Grosso and thereby highlight the importance of understanding farmer adoption decisions and responses to changes in financing conditions, especially in situations with high rates of interest and inflation which Brazil currently faces.

Transaction and learning costs associated with adopting new agricultural practices and on-farm technologies influence farmer land-use decisions. Such barriers, economic benefits of innovation and externally provided economic incentives (i.e., ABC credit) altogether constitute the factors determining the actual diffusion of agricultural innovations (Lee 2005). Our microsimulation approach accounts for innovation benefits and different forms of additional incentives but does not (yet) account for the bureaucratic and social barriers to integrated system adoption found by Gil et al. (2015). Therefore, the simulation results here should be interpreted as the upper limit of integrated system adoption once these barriers have been removed.

It is possible to include these barriers into agent-based simulation by following the approach of Schreinemachers et al. (2010) and simulate the resultant adoption patterns – which will be done once the required empirical data from ongoing field data collection are available. Work is also ongoing to parameterize disaggregated GHG balances in our bioeconomic modeling approach, by integrating MPMAS_MONICA with a third model component CANDY (Carbon and Nitrogen Dynamics) based on field experimental data. We will then be able to extend our bioeconomic modeling approach and simulate changes in GHG emissions and carbon abatement costs in Mato Grosso.

Chapter 8. Assessing policy measures to reduce greenhouse gas emissions from crop, livestock and commercial forestry plantations in Brazil's Southern Amazon

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This chapter has been submitted to Agricultural Economics in August, 2018. A previous version of it has been published[10] in the Proceedings of the 30th International Conference of Agricultural Economics.

Abstract

This study assesses the full distribution of greenhouse gas (GHG) emissions related to agricultural land-use change in Mato Grosso, Brazil, both from farmer and climate policy perspectives. By combining three simulation models as well as data from field experiments and literature, we present a novel Integrated Assessment (IA) 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 evaluate the farmer policy response to the ABC Credit Program that the Brazilian government has launched for promoting low-carbon farming. In terms of carbon footprint, our simulations show that the largest source of GHG emissions from crop and eucalyptus production is the use of farm inputs while for cattle production it is emission from enteric fermentation. The results of our simulations indicate that the ABC Integration credit line, under current conditions, indeed contributed to the adoption of less GHG-emitting practices on cropland areas in Mato Grosso.

[10] Carauta, M., Guzman-Bustamante, I., Meurer, K., Hampf, A., Troost, C., Rodrigues, R., Berger, T., 2018. Assessing the full distribution of greenhouse gas emissions from crop, livestock and commercial forestry plantations in Brazil's Southern Amazon, in: Proceedings of the 30th International Conference on Agricultural Economics. 30th International Conference on Agricultural Economics, Vancouver, Canada.

However, in a significant number of cases the policy had no impact on GHG emissions and, in some cases, it induced maladaptation (an increase in GHG emissions).

8.1. Introduction

In 2009, the Brazilian government 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 (Ministry of Science, Technology and Innovation 2016)) the government implemented the ABC Plan (low-carbon agriculture plan, in Portuguese, "Plano de Agricultura de Baixo Carbono") in 2010. The ABC Plan supports the adoption of low-carbon agricultural practices by offering – among other measures – loans with subsidized credit for farmers. Reports from Observatório ABC (2016) – an initiative aiming to engage society in the debate on low-carbon agriculture – however, argue that the program has not achieved its full potential. During the 2015/2016 cropping season, the program only lent 68% of the total amount made available by the federal government (Observatório ABC 2016).

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 agricultural production systems) as a strategy to reduce environmental impacts and 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 (Hanson and Franzluebbers 2008; Hendrickson et al. 2008b).

Despite the potential benefits of IAPS, the adoption of integrated systems by farmers in Mato Grosso (MT) is still slow and the reduction in terms of GHG emissions largely unknown. Recent literature on GHG emissions is increasing but there are only few empirical studies applied to MT. Cerri et al. (2016) evaluated the main sources of GHG emission in beef production systems for 22 farms in Mato Grosso, while Rodrigues 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 more fully capture the heterogeneity of climate, soil type, and cultivation systems (Prudêncio da Silva et al. 2010). In addition, LCA approaches are, usually, data-hungry, might be subjected to boundary issues and do not provide design alternatives, which are crucial to an holistic assessment (Jusselme et al. 2018).

Therefore, we aim to contribute to the current literature by introducing a novel approach that evaluates a large variety of real-world agricultural production system at farm level. We advance the modeling approach of Carauta et al. (2017a) and Hampf et al. (2018) and combine an agent-based bioeconomic model with mathematical programming and life cycle inventory to simulate land use, farm-level decision-making and GHG emissions.

Through computer simulation, we evaluate the effectiveness of the ABC credit line in reducing GHG emissions by the adoption of IAPS, highlight remaining knowledge and data gaps and identify future research priorities.

8.2. Methods and Data

8.2.1. 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 (Brazilian National Supply Company 2017). Ecologically, MT has three different ecosystems, the Amazon rainforest, the swampy Pantanal (wetland) area, and the Cerrado “bushland” that comprises approximately 60% of the state’s native forest area (Instituto Mato-Grossense de Economia Agropecuária 2017).

As described in Carauta et al. (2017a) and Hampf et al. (2018), we followed the sampling procedure of Instituto Mato-Grossense de Economia Agropecuária (2010a) and parameterized our simulation models for five macro-regions in Mato Grosso: West, Mid-North, Southeast, South Central and Northeast. 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 fertilizer 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 application frequencies and quantities. A crop calendar with weekly resolution was created to capture the timing of agricultural activities at each survey site of Mato Grosso Institute of Agricultural Economics (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 2,000 crop-mix options at farm level. The complexity of farmer decision-making increases even further as favorable climatic conditions now allow for 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 they 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).

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 only produces wood and has a 14-year production cycle.

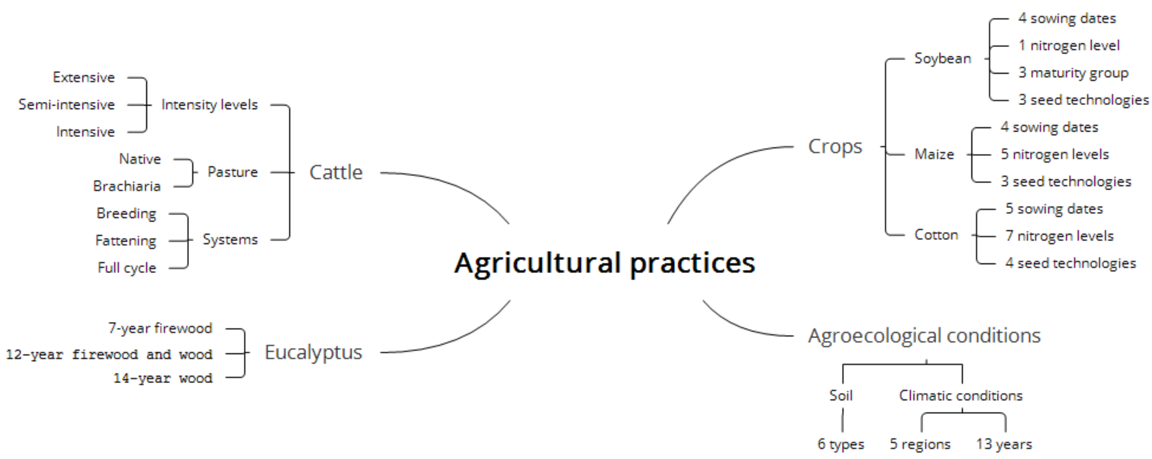


Figure 8.1 *Overview of agricultural practices*

8.2.2. Production systems observed in Mato Grosso

Costs and benefits of local production systems were estimated for the study region according to the IMEA agricultural production cost survey (Instituto Mato-Grossense de Economia Agropecuária 2013b), the planted forests report of Mato Grosso (Federação da Agricultura e Pecuária do Estado de Mato Grosso 2013), Mato Grosso's cattle ranching report (Instituto Mato-Grossense de Economia Agropecuária 2016b) and with local experts. For example, typical soybean, maize and cotton production at Sorriso (Mid-North region in MT) have the following agricultural practices, respectively: sowing dates (01/Oct, 06/Feb and 15/Jan), nitrogen fertilizer amount (0 kg/ha, 80kg/ha and 185 kg/ha), varieties (Herbicide Tolerant, Insect Resistant for maize and cotton) 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 production system, which considers two practices, breeding and fattening. Both extensive systems have the following characteristics: 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). Lastly, a typical forestry production system focuses on firewood production in a seven-year cycle.

8.2.3. 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 on cropland under consideration of resource availability, agroecological constraints, and GHG emissions. As depicted in Figure 8.2, 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).

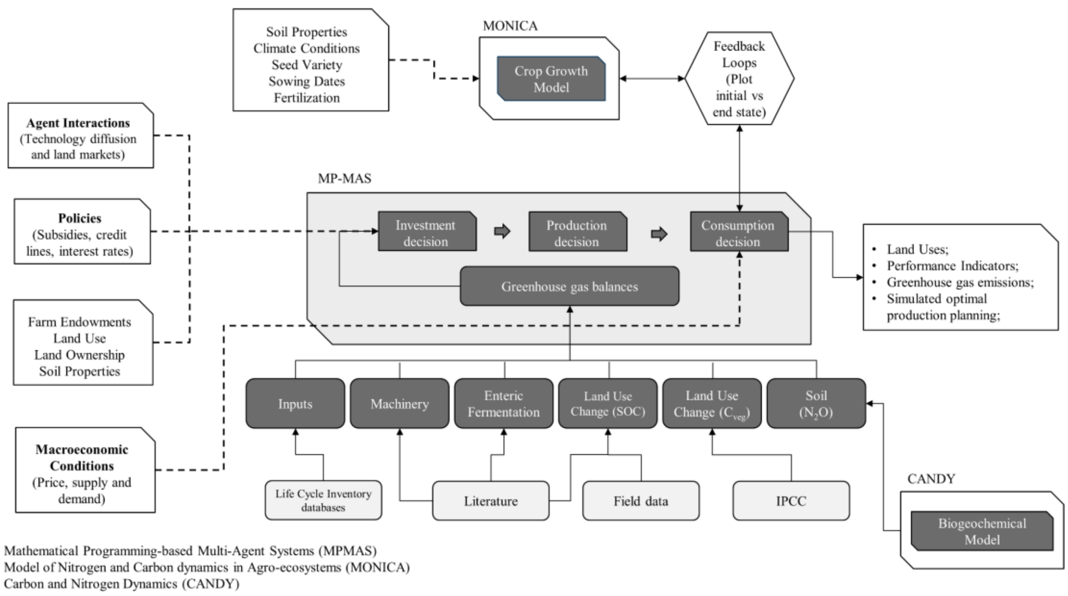


Figure 8.2 *Model flowchart and data sources*

We advance the modeling approach published in Carauta et al. (2017a) and Hampf et al. (2018) by incorporating life-cycle GHG balances in our present simulations. Since a detailed explanation of model parameterization and model validation is already available in those articles, 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. For more detail, the reader is referred to the online supplementary material.

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). For this current application, a statistically consistent agent population was created for the study region as described in Carauta et al. (2017a). 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 at individual farm level 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 actual 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 nitrous oxide (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 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 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 in soil carbon stocks (and resulting CO_2 fluxes) were included in our current simulations.

Based on the crop management decisions in MPMAS and the resulting crop yields simulated by MONICA, CANDY simulates daily nitrous oxide (N_2O) fluxes by taking into consideration all production systems at farm agent 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.

8.2.4. Specific LCA data

Based on the approach proposed by Castanheira and Freire (2013), we established a life cycle GHG inventory for agricultural production systems implemented for farms in MT. The system boundary was "cradle to farm gate" and GHG emission factors were estimated for agricultural 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 emissions 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 (e.g. soil amendments, seeds, adjuvants, animal feed) are retrieved from the carbon footprint app CCaLC V2.0 (Azapagic 2017) and the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model - GREET Model – database (Argonne National Laboratory 2015), accounting for the carbon footprints from “cradle to farm gate”. Emissions from machinery production are calculated according to Rotz et al. (2010) and take into consideration machinery mass and are amortized by lifetime. Emissions due to diesel combustion are calculated as a function of machinery horsepower and a diesel consumption factor – estimated by the Brazilian National Supply Company (Brazilian National Supply Company 2010) – and takes into consideration the emission factor for diesel production and combustion as well as the diesel density.

Nitrous oxide emissions from soil microbiological processes (nitrification and denitrification) 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. 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 feces 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), only 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 a eucalyptus plantation in a 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 the 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 over 20 years, as recommended by Flynn et al. (2012), and converted to kilograms of CO_2e per year and hectare. Since farm agents in our current modeling setup 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 (Eggleston et al. 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 for 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 Anuário da Pecuária Brasileira (2013) - and multiplying it to carcass yield (which is estimated by local experts and depends also on the 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 (e.g. extensive production systems), while managed pasture land use refers to production systems with fertilizer application (e.g. semi-intensive and intensive systems). SOC stocks for eucalyptus plantation were taken from field experiments in Minas Gerais state since there was no available data for MT. Our simulation experiments take into consideration six different soil types, but empirical data on SOC stocks and soil emissions for eucalyptus were only available for one (ferrosol 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.

8.2.5. Simulation: scenarios for policy analysis and experimental design

For policy impact analysis, we designed two scenarios to assess the potential contribution of the ABC Integration credit line in increasing the adoption of low emission practices. This was done by comparing a baseline scenario [ABC] – which reflects the situation in which all model agents have access to ABC Integration credit line (but may decide not to take it) – with a counterfactual scenario [NO_ABC] where no subsidized credit is made available to the model agents. At the time of our analysis, 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 (in Brazilian Reais) totaled three million for forestry and two million for integrated systems (for further details, refer to Carauta et al. (2017a)).

Since our IA application is subject to uncertainty associated with model inputs (parameters and exogenous variables), an uncertainty analysis (UA) was carried out to evaluate the robustness of our simulation results. We identified 19 main uncertain parameters in our modeling approach, which are grouped into four categories: selling prices, input prices, yields and emission factors. Prices and yields as well as selling prices and input prices are highly correlated (in the latter case, due to a common dependence on US dollar exchange rates). To maintain this correlation, 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 prices and yields from that year in the respective model run. Local prices were corrected for inflation and market trends.

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 (simulated GHG emission) and each scenario was simulated using the same Sobol' sequence of parameters (Berger et al. 2017; Troost and Berger 2015). When testing for model convergence, we found out that 60 repetitions are enough in our case to make the mean and the 5th and 95th percentile of the simulated GHG reduction over the sequence converge to a stable value.

8.3. Simulation Results

In this section, we present the results of our Integrated Assessment approach. Subsection 8.3.1 presents the simulated carbon footprints for typical production systems in MT while subsection 8.3.2 presents a complete analysis of our findings with the full distribution of GHG balances for all combinations of region-specific agricultural practices. Then, an impact assessment analysis with all farm agents is presented in section 8.3.3.

8.3.1. The carbon footprint for typical production practices in Mato Grosso

Figure 8.3 summarizes the simulated total GHG emissions from typical agricultural practices (see above in section 8.2.1) for different sources: enteric fermentation, agricultural inputs, CVEG and SOC (change in carbon stocks above and below ground), machinery and fuel, and nitrification and denitrification. 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 (previous cropland is afforested). Cropping systems presented have a positive net balance of GHG emissions since there is no sequestration 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, CVEG and SOC emissions.

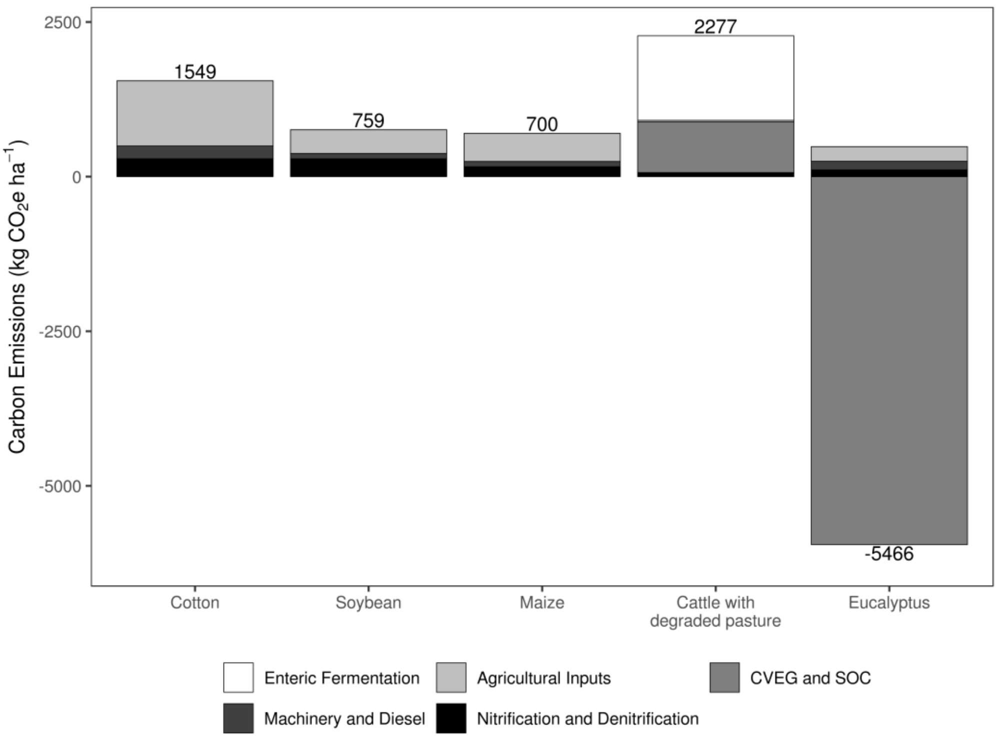


Figure 8.3 *Simulated total GHG emissions for typical production systems in Mato Grosso. Note: Balances refer to cropland as previous land use. CVEG = Carbon stock from vegetation, SOC = Soil organic carbon.*

8.3.2. Primary GHG emissions for production practices in Mato Grosso

Figure 8.4 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 (nitrification and denitrification). Large variation can be observed for most of the production systems. The large variation of GHG emissions in cattle production is due to the heterogeneity of intensity levels (e.g. 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.

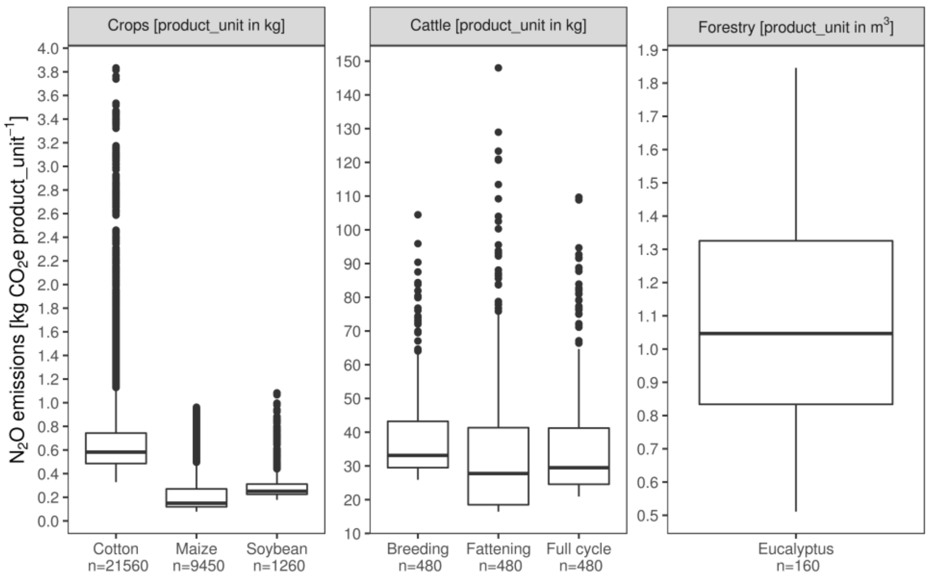
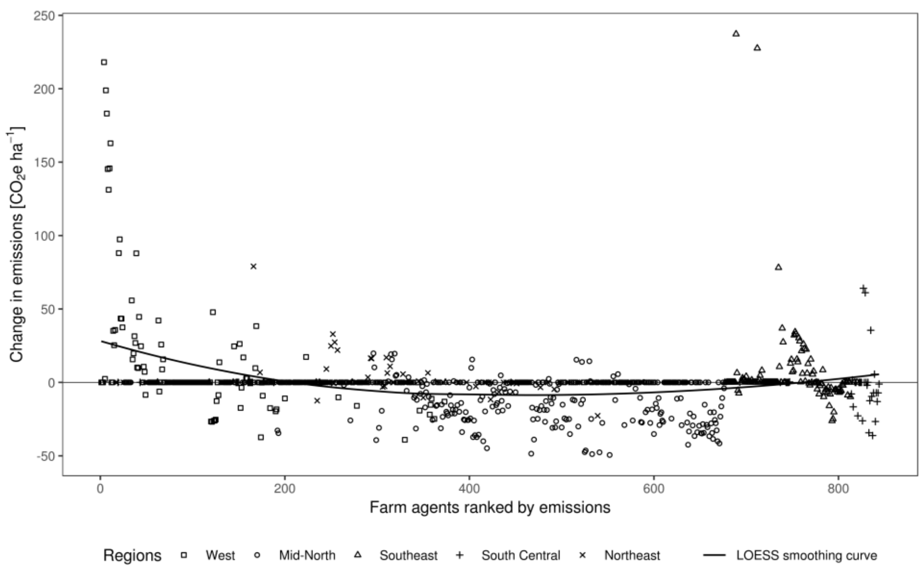


Figure 8.4 *Simulated GHG emissions in carbon dioxide equivalents per product unit for different production systems (n = number of observations).*

8.3.3. Greenhouse gas emissions and the adoption of subsidized credit for low-carbon agriculture

In our policy analysis experiments, we simulated the impact of the ABC credit on reducing GHG emissions. To assess the effect of ABC credit, we compared the baseline scenario [ABC] with the counterfactual scenario [NO_ABC] over 60 repetitions. Figure 8.5 ranks the individual farm agents by their average GHG emission over all repetitions and years. We found that about 66% of agents who took on ABC credit, on average, emitted less GHG in the baseline scenario with the ABC credit, while for 3% of agents the ABC credit line had no impact on GHG emissions and for 31% of agents there was an increase on GHG emissions.



Note: Individual agent emissions were averaged over all repetitions and years and then ranked by their emission in the counterfactual scenario [NO_ABC].

Figure 8.5 *GHG emission change in the baseline [ABC] compared to counterfactual scenario [NO_ABC].*

A closer look on all cases simulated (e.g., 844 agents in 60 repetitions and 3 years in both scenarios) reveals that 57% of ABC credit adopters reduced their GHG emissions, 33% increased emissions while 10% had no change in emission levels. To unravel this uncertainty of policy impacts at farm level, we further disaggregated the effects to distinguish the incidence of cases where policy interventions led to increasing GHG emissions. Our simulations show that expected favorable market conditions (such as higher expected prices and crop yields) were the main factors contributing to increased GHG emissions. Higher prices and yields led farm agents to change their production systems to more emitting practices. In addition, once the ABC credit line was introduced, some agents (e.g. agents at the top of Figure 8.5) used their additional liquidity to invest in machinery and increase their cropland share and, thus, emitting more than in the counterfactual scenario [NO_ABC].

8.4. 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 level. It is important to point out that our findings, however, 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 not (yet) available to parameterize all production activities, management practices, and agronomic conditions. Instead, assumptions were made to fill those data gaps (section 8.2.4). Therefore, one must take these assumptions into consideration when evaluating our results. Nonetheless, we achieved high levels of model efficiency and we are confident that our models provide realistic results and allow a further understanding on the full distribution of GHG emissions and to draw conclusions on the effectiveness of ABC credit lines.

Our median GHG emissions of soybean production lie above the one estimated by Raucci et al. (2015) but agree in identifying agricultural inputs (fertilizer and pesticides) as the main source of GHG emissions, followed by nitrification and denitrification, 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 can capture the heterogeneity of individual farm holdings together with their specific agroecological constraints. We, therefore, agree with Raucci et al. (2015), who admits that the majority of LCA studies in Brazil employ crop management data based on national averages or public databases, which do not represent the full picture of a region's reality.

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 as 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 animal feeding. Figure 8.3 confirms this by displaying enteric fermentation as the main source of primary emission (without CVEG and SOC) in cattle production.

In terms of CVEG and SOC 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 add 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).

In Brazilian soils, eucalyptus plantations have increased SOC stocks, when previous land use was savanna or grassland, while a decrease in SOC stock took place when rainforest was the preceding land use (Fialho and Zinn 2014). Our results show a net carbon sequestration for SOC when land-use changes from cropland to eucalyptus plantations, which is in accordance with findings of Rangel and Silva (2007).

The results of our simulation suggest that ABC credit indeed contributed to reducing GHG emissions on cropland areas in MT. Without considering possible bureaucratic and social barriers at farm level, the subsidized credit line was accessed on 18% of cases (844 agents over 60 repetitions and 3 years simulated in both scenarios) and 57% of adopters emitted less GHG emissions in the baseline scenario.

Our uncertainty analysis shows that agent price and yield expectations clearly affect the climate policy impacts of ABC credit. As a result, with the current framework, the ABC credit line in our simulations could not reach its full potential and its performance was subjected to variation of prices and yields.

In addition, in 7% of simulated cases, the introduction of subsidized credit line induced maladaptation and thereby increased GHG emissions. Among these cases, a large share (87%) consisted of farm agents who had already adopted some type of IAPS in the counterfactual scenario [NO_ABC] but, once the credit was introduced, used their extra liquidity to increase their cropland and emitted more. In these cases, the policy intervention gave undesired incentives to farm agents who were already IAPS adopters. Our uncertainty analysis additionally shows that maladaptation occurred more often in years where expected crop (especially cotton, due to its high economic returns) prices and yields were higher in comparison to cattle and forest production systems.

Our results show that there is still room for improvements for ABC Credit Program. Agents took on ABC credit only in 18% of all simulated cases (844 agents over 60 repetitions and 3 years simulated in both scenarios). In 82% of all simulated cases (and 10% if we consider only credit adopters) we could not observe any changes on GHG emissions. These results combined suggest that the incentive mechanism from this policy intervention is not strong enough for a significant number of cases.

Therefore, we argue that the current credit framework is too broad and more targeted policy interventions are needed in Brazil to address those issues. In addition to land use shares, management practices and crop/product-oriented setups could be used to increase policy impacts. We also suggest that policy assessment in Brazil should not only rely upon the supply of credit - as applied in Observatório ABC (2016) - and/or average effects of interventions – as applied in Lima and Gurgel (2017) and Observatório ABC (2017). These assessments do not capture individual farmer responses and may overlook the losses due to potential gains from a group of agents. Thus, we argue that policy interventions in MT should take into consideration agent heterogeneity and decision-making into account.

Our simulations do not (yet) account for synergy effects of integrated production systems. From the farmer's perspective, there is still a high degree of uncertainty regarding access to information and knowledge for IAPS adoption (Gil et al. 2016). From a researcher's point of view, Garrett et al. (2017) state that the currently available baseline empirical data is critical to increasing the sophistication and multi-disciplinarity of modeling efforts related to IAPS.

We expect to tackle these limitations in the future by extending our uncertainty and sensitivity analysis, in order to evaluate the role of synergy effects on IAPS adoption and on land use change. This could provide important information regarding potential synergy effects and help researchers (since with a simulation experiment one can assess which configuration of IAPS might be more likely adopted by farmers) and farmers (since it might lead to better understanding of the economic performance of different IAPS setups vis-à-vis exclusive production systems).

8.5. Conclusions

The ABC Credit Program is the main credit line available to Brazilian farmers to finance the goals and technologies advocated by Brazil's low-carbon agriculture plan. Since its introduction in the year 2010, however, the ABC Credit Program never achieved its projected potential, reporting slow credit uptake over the years. To ensure the achievement of emissions-reduction targets pledged by the ABC Plan, monitoring actions have been planned but, to date - 7 years after -, these are still at an initial stage.

For this reason, this article presents an innovative approach for evaluating GHG emissions from crop, livestock, and commercial forestry plantations and to simulate the ABC credit line performance in terms of GHG reduction. We applied a novel Integrated Assessment approach to simulate GHG balances in a globally important hot-spot of agricultural production and biodiversity. To the best of our knowledge, this is the first study in MT to evaluate ABC Credit Program at farm level considering economic decision-making and environmental heterogeneity. 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.

Our simulation results point to several important findings. First, the results of our simulations suggest that the ABC Integration credit line indeed contributed to the adoption of agricultural practices with lower GHG emissions. In terms of carbon footprint, the results indicate that the GHG balance at farm level is highly dependent on the proceeding land use. The largest source of GHG emissions for crop production is the use of agricultural inputs while the largest share of GHG emissions in cattle production is from enteric fermentation.

Second, 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 quantify 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.

Third, it suggests that the effectiveness of ABC Credit Program is quite different across the farmer population. Particularly, IAPS adopters had the incentive to change production systems with higher emissions. Moreover, initial farm locations (and, therefore, its soil characteristics and climatic conditions) and asset endowments (such as machinery quantities) are strong factors influencing the policy outcome.

Fourth, we found the ABC policy performance is subjected to agent expectations regarding environmental/market conditions since the expected profitability between production systems was the main factor influencing the decision-making. Fifth, we found a significant number of simulated cases where the subsidized credit line had no impact on GHG emission or was not attractive enough to farmers. Lastly, we also found several cases where policy uptake led to maladaptation (an increase in GHG emissions). Altogether, we underline the importance of policy recommendation which takes into consideration farmer heterogeneity and decision-making rather than average indices that may mislead policymakers to introduce interventions which are only beneficial for typical farms but ineffective in a heterogeneous region (such as MT).

Discussion and conclusions

The previous chapters showed different studies related to land use change and adoption of sustainable agricultural systems in Mato Grosso, Brazil. The first part (chapters 1, 2 and 3) offered an overview of land use change and deforestation in Brazil and explored the trade-offs of different agricultural practices in double cropping systems. The second part (chapters 4 and 5) introduced our integrated assessment approach and presented two applied study cases that evaluated alternative options to improve farming systems in MT. The third part (chapters 6, 7 and 8) was dedicated to investigating the adoption of low-carbon agricultural systems and evaluate how policy measures can speed up their adoption.

Even though farmers in MT are among Brazil's most productive producers of soybean, maize, and cotton, few studies have addressed the crop yield response to biophysical constraints (e.g., sowing dates, fertilization amounts, and soil characteristics). Existing studies in MT usually rely on field experiments that are often not replicable to other macro-regions and not repeated over several cropping seasons or crop varieties. This thesis presents the first extensive study on crop yield response in MT by simulating yields in response to different climatic conditions, soil types, sowing dates, crop rotation schemes, fertilization amounts, and macro-regions. Furthermore, this thesis estimates the magnitude of yield gaps - between potential and actual yields - in MT and decompose them into their biophysical and socio-economic dimensions. The simulation results show that biophysical constraints (due to water and nutrient deficit) account for 24% of potential yields whereas socio-economic constraints account for 6%.

This thesis further examines alternative ways to improve the farming systems in MT by investigating the role of sunflower adoption in increasing farm income. Previous studies on technology adoption in MT have only focused on field experiments or typical farms and, therefore, failed to capture farm heterogeneity and to assess the technological diffusion at the regional level. For this reason, this thesis introduces a novel solution for evaluating dynamic and complex farming systems on heterogeneous regions and offers a comprehensive analysis of sunflower adoption on both farm and regional level. We have found a substantial potential for sunflower cultivation in MT with positive impacts on both farm and regional level and identified bottlenecks for its diffusion (such as the distance from farm gate to processing facility).

Regarding Brazilian agricultural policy, in 2010 the national government implemented the low-carbon agriculture program which supports - among other measures - the adoption of integrated agricultural systems. So far, the estimation of integrated systems adoption is done by a few field surveys (that are costly and limited), and policy performance is estimated from the supply side (amount lent divided by the total amount made available by the federal government). We also found our model agents to be sensitive to changes in financing conditions. Furthermore, since the return of integrated systems is – in some cases – slightly higher than conventional systems, we found that small changes in financing can trigger larger reallocation of financial resources between competing land uses and credit sources

With respect to GHG emissions, existing studies are scarce and normally considers only the most typical agricultural practices or a few numbers of farms. For this reason, we developed a model that can simulate the adoption of integrated systems in MT and consider farmers economic incentives and decision-making. Also, we provide a detailed quantification of carbon footprints from a large variety of agricultural practices and, further, estimate the aggregate emissions resulting from their current use in MT. We have found that the ABC program contributed to the adoption of integrated systems, but with different adoption rate through macro-regions and types of integrated systems. Furthermore, our simulations additionally show that the ABC program also contributed to the adoption of less GHG-emitting practices, but its performance is subjected to agent expectations on prices and yields. Another important implication is that the GHG balance at farm level is highly dependent on the proceeding land use. This information can be used to develop targeted interventions aimed to preserve native vegetation and restore degraded pastures. Our simulations enhance the understanding of carbon footprints by revealing that GHG emissions are sensitive to several social and environmental variables/constraints which are (so far) difficult to quantify in current LCA studies, which usually rely on typical production systems and therefore overlook these crucial aspects.

Model limitations. Since our results are estimated based on simulation experiments, they are also subjected to data availability and quality constraints. Since no robust data on potential and water-limited yields at farm level was available, MONICA was calibrated to actual farmer yields. Nonetheless, the comparison of simulated and observed crop yields indicated that the performance of MONICA is within acceptable limits. Due to lack of data, our current simulation does not account for the bureaucratic and social barriers to integrated systems and sunflower adoption and, therefore, our simulation results should be interpreted as the upper limit of their adoption. With respect to sunflower, since our focus was to simulate its potential adoption and production, we did not consider MT's current processing capacity.

Another limitation at the modeling stage was that emission factors could not be found for all agricultural inputs and production practices and, instead, assumptions were made to fill those data gaps. Still, we are confident that our model provides realistic results since high levels of model efficiency were achieved and the results from current literature lie within our estimations. To evaluate the robustness of our simulation results, an uncertainty analysis was carried out, and a fully controlled experiment that isolates the scenario effect on each agent from any variation in other parameters was created.

Future research. The first part of this thesis focused on understanding the determinants of land use change and the economic trade-off on agricultural systems in MT. Further work needs to be done to determine the influence of biophysical conditions on grasslands due to the significant share of degraded grasslands in MT – and the high level of GHG emissions related to this land use. The second part of this thesis focused on evaluating alternative options to improve farming systems in MT. A lot of effort went into the parameterization of the biophysical model component. Still, further investigation and experimentation at farm-level are needed to improve model accuracy and to assess the long-term effects of integrated systems synergy effects and GHG emission factors for MT conditions. This could provide valuable information regarding potential synergy effects and help researchers (since with a simulation experiment one can assess which configuration of integrated systems might be more likely adopted by farmers) and farmers (since it might lead to better understanding of the economic performance of different integrated systems setups vis-à-vis exclusive production systems).

For agricultural land use, further research is needed to account the impact of climate change and to evaluate alternative options for climate change adaptation. Concerning sunflower land use, it would be interesting to assess the impact of current processing facilities on sunflower adoption and to investigate the market response to maize and sunflower production, since these two crops compete in land use at the second season. A natural progression of this work is to analyze cases for effective policy intervention to promote sunflower adoption in MT.

Another relevant issue for future research is the sustainable intensification of Brazilian livestock production. Since livestock systems are dynamic and require long-term decisions, further work is required to switch from stationary equilibrium mathematical programming approaches to multi-period approaches that can capture the dynamic of herd sizes over time, simulate relevant decisions for each period and estimate the net present value of costs and returns over the entire planning horizon. Furthermore, once robust data on grasslands is available, one could parameterize a grass growth model to assess how do changes in sowing dates, fertilization, climatic conditions and soil characteristics affect grassland yields in MT.

The results of this thesis support the idea that preferential credit line can promote the adoption of low-carbon agricultural systems. For instance, a future study investigating to which extent synergy effects can determine the adoption of integrated systems would be very interesting. Further research needs to examine more closely the links between integrated system adoption and risk mitigation. Even though risk mitigation is one of the most significant advantages of integrated systems, few studies have investigated it.

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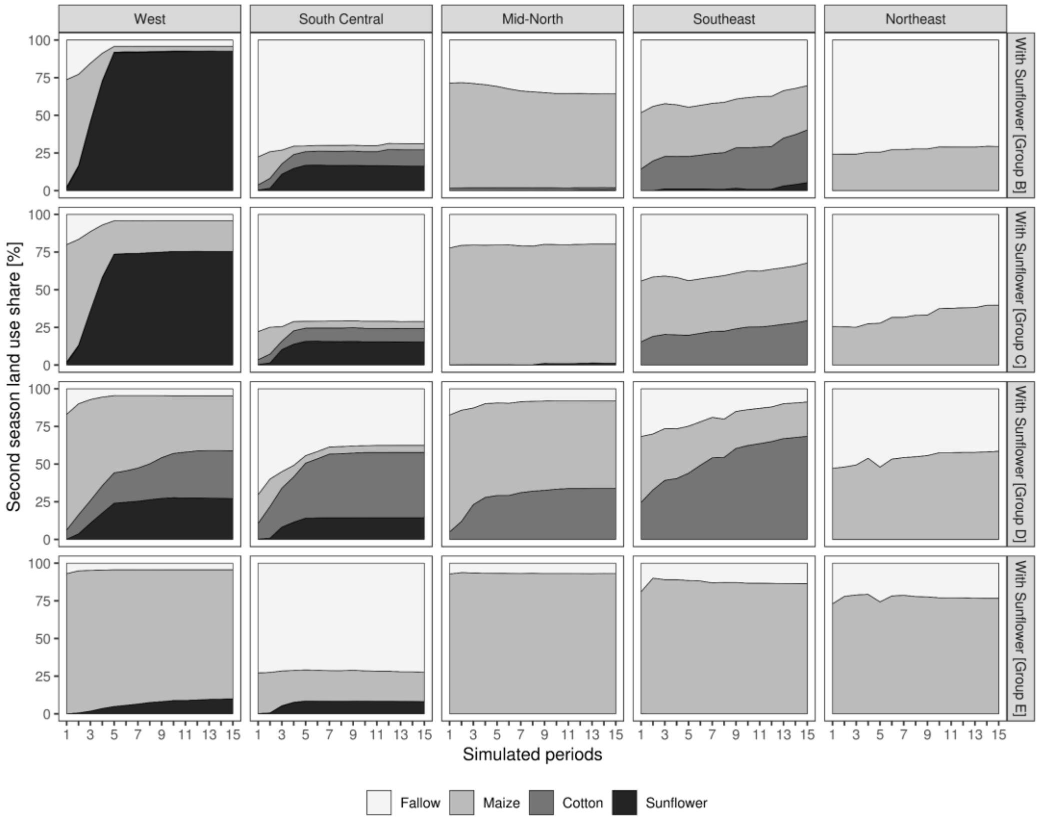
Appendix

Land-use allocation at the second cropping season for groups B, C, D and E.



Reference list for Table 6.1 and Table 6.2

[1] Macedo (2009)

[2] Balbino et al. (2011)

[3] Gil et al. (2015)

[4] Carvalho et al. (2014)

[5] Assmann et al. (2004)

[6] Flores (2004)

[7] Chan (1985)

[8] Salton et al. (2014)

[9] Chioderoli et al. (2012)

[10] Balbino et al. (2012)

[11] Martha Jr. et al. (2010)

[12] Landers (2007)

[13] Cobucci et al. (2007)

Author's Declaration

Affidavit

pursuant to Sec. 8(2) of the University of Hohenheim's doctoral degree regulations for Dr.sc.agr.

1. I hereby declare that I independently completed the doctoral thesis submitted on the topic
   "*Assessing alternative options to improve farming systems and to promote the adoption of low-carbon agriculture in Mato Grosso, Brazil*".
2. I only used the sources and aids documented and only made use of permissible assistance by third parties. In particular, I properly documented any contents which I used - either by directly quoting or paraphasing - from other works.
3. I did not accept any assistance from a commercial doctoral agency or consulting firm.
4. I am aware of the meaning of this affidavit and the criminal penalties of an incorrect or incomplete affidavit. I hereby confirm the correctness of the above declaration.

I hereby affirm in lieu of oath that I have, to the best of my knowledge, declared nothing but the truth and have not omitted any information.

……………………… ………………………………

(Place, date) (Signature)

Affidavit

Information

The University of Hohenheim requires an affidavit declaring that the academic work was done independently in order to credibly claim that the doctoral candidate independently completed the academic work.

Because the legislative authorities place particular importance on affidavits, and because affidavits can have serious consequences, the legislative authorities have placed criminal penalties on the issuance of a false affidavit. In the case of wilful (that is, with the knowledge of the person issuing the affidavit) issuance of a false affidavit, the criminal penalty includes a term of imprisonment for up to three years or a fine.

A negligent issuance (that is, an issuance although you should have known that the affidavit was false) is punishable by a term of imprisonment for up to one year or a fine.

The respective regulations can be found in Sec. 156 StGB (Criminal Code) (false affidavit) and in Sec. 161 StGB (negligent false oath, negligent false affidavit).

Sec. 156 StGB: False Affidavit:

Issuing a false affidavit to an authority body responsible for accepting affidavits or perjury under reference to such an affidavit shall be punishable with a term of imprisonment up to three years or with a fine.

Sec. 161 StGB: Negligent False Oath, Negligent False Affidavit:

Subsection 1: If one of the actions described in Secs. 154 and 156 is done negligently, the action shall be punishable by a term of imprisonment of up to one year or a fine. Subsection 2: Impunity shall apply if the perpetrator corrects the false information in a timely manner. The regulations in Sec. 158 (2) and (3) apply mutatis mutandis.

The German original version of this affidavit is solely valid; all other versions are merely informative.

I have taken note of the information on the affidavit.

……………………… ………………………………

(Place, date) (Signature)

Curriculum Vitae

Marcelo Carauta Montenegro Medeiros de Moraes

Personal Data

Date of birth 29.07.1985 - Rio de Janeiro - Brazil
Nationality Brazilian
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Education

Since 04.2015 **Ph.D. candidate at the Department of Land Use Economics in the Tropics and Subtropics**
Universität Hohenheim (UHOH), Stuttgart, Germany
Title: Assessing alternative options to improve farming systems and to promote the adoption of low-carbon agriculture in Mato Grosso, Brazil
Supervisor: Thomas Berger
Scholarship from: Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES)

03.2007 – 12.2008 **Master's in Economics**
Federal Fluminense University (UFF), Niterói, Brazil
Title: The impact of new information on financial markets: An analysis of American and Brazilian stock markets
Supervisor: Helder Ferreira de Mendonça

01.2009 – 12.2009 **MBA in Financial Analysis**
Gama Filho University (UGF), Rio de Janeiro, Brazil
Title: The impact of new information on financial markets
Supervisor: Ana Cristina Benavente

03.2003 – 12.2006 **Bachelor in Economics**
Getúlio Vargas Foundation (FGV), Rio de Janeiro, Brazil

Professional Experience

Since 07.2016 **Research Assistant – Hohenheim University**, Dept. of Land Use Economics in the Tropics and Subtropics (Hans-Ruthenberg-Institute), Stuttgart, Germany:
At Hohenheim University my work focused on writing project reports, teaching tutorial classes for Farm System Modeling module and mentoring students on how to write scientific papers in Agricultural Economics Seminar module. I also assisted our team in testing, implementing and documenting new features at our MPMAS (Mathematical Programming-based Multi-Agent Systems) software. I was also responsible for establishing and maintaining collaborative research projects within the topic of modeling the adoption of sustainable production systems.

01.2011 – 02.2015 **Researcher – Brazilian Agricultural Research Corporation (EMBRAPA)**, Integrated Agricultural Systems (IAS) research station, Sinop, Brazil:
At EMBRAPA my work focused on researching the economic impacts of IAS adoption. I was in charge of writing research project proposals and project reports, supervising data collection on field trials, estimating production cost and economic

performance of different production systems and technologies. During this time, I worked on a total of twelve research projects and supervised one as its leader. My major research topics were: IAS adoption, financial management in rural properties, biochar adoption, improved technologies for soy, maize and sorghum production systems, adoption of agroforestry systems and native forest restoration.

06.2012 – 10.2013 **Lecturer – FASIPE University (University of Sinop)**, Sinop, Brazil:
At FASIPE I participated in two MBA programs (Financial Management and Agribusiness Management) and lectured the following modules: Financial Indicators and Investment Analysis, Stock Markets, Agricultural Commodity Markets, Economics of Agricultural Markets and Foundations of Finance.

08.2013 – 12.2014 **Lecturer – La Salle University**, Sorriso, Brazil:
At *La Salle* University I participated in one MBA program (Strategic Management) and lectured the following modules: Corporate Finance and Advanced Financial Methods with Excel and HP 12C.

03.2011 – 09.2013 **Lecturer – Cuiabá University (UNIC)**, Sinop, Brazil:
At UNIC I participated in one MBA program (Agribusiness Management) and two Bachelor programs (Accounting and Business Administration) and lectured the following modules: Macroeconomics, Economics, Future Markets, and Financial and Capital Markets.

02.2009 – 12.2010 **Financial Analyst – Ático Asset Management**, Rio de Janeiro, Brazil:
At *Ático* I worked with stock market trades, mostly with transactions in future markets (Dollar, Stock Index, Interest Rate Bonds), options (Dollar and Stocks). I was also in charge of risk reports, fund management, macroeconomic analysis, and portfolio monitoring.

04.2008 – 02.2009 **Junior Risk Analyst – Opus Asset Management**, Rio de Janeiro, Brazil:
At *Opus* I worked with asset pricing, portfolio management and risk evaluation, such as market/macroeconomic analysis and estimation of risk indicators (e.g. Stress Tests and Value-at-Risk - VaR).

01.2007 – 03.2007 **Junior Financial Broker – Concórdia**, Rio de Janeiro, Brazil:
At *Concórdia* I worked with transactions in future markets (Dollar, Index and Interest Rate) and relationship with customers (e.g. Banks and Investment Funds).

06.2005 – 12.2006 **Economist – Safety Insurance Brokerage**, Rio de Janeiro, Brazil:
At *Safety* I worked with insurance pricing and sales as well as relationship with customers and insurance companies.

List of publications

Journal contributions

Carauta, M., 2016. Combating deforestation in the Brazilian Amazon: options for national and global governance. International Journal of Agriculture and Environmental Research. 2, 17.

Carauta, M., Latynskiy, E., Mössinger, J., Gil, J., Libera, A., Hampf, A., Monteiro, L., Siebold, M., Berger, T., 2017. Can preferential credit programs speed up the adoption of low-carbon agricultural systems in Mato Grosso, Brazil? Results from bioeconomic microsimulation. Reg Environ Change. 27, 675.

Carauta, M., Libera, A., Hampf, A., Chen, R., Silveira, J. M., Berger, T., 2017. On-Farm trade-offs for optimal agricultural practices in Mato Grosso, Brazil. Revista de Economia e Agronegócio (Brazilian Journal of Economy and Agribusiness). 15, 299–322.

Dantas, I., **Carauta, M.**, 2016. Why should farmers in Brazil change to Integrated Agricultural Production Systems? International Journal of Agriculture and Environmental Research. 2, 18.

Hampf, A. C., **Carauta, M.**, Latynskiy, E., Libera, A. A.D., Monteiro, L., Sentelhas, P., Troost, C., Berger, T., Nendel, C., 2018. The biophysical and socio-economic dimension of yield gaps in the southern Amazon – A bio-economic modelling approach. Agricultural Systems. 165, 1–13.

Oliveira Júnior, O. L. O., Carnevalli, R. A., Peres, A. A. C., Reis, J. C., **Carauta, M.**, Pedreira, B. C., 2016. Economic and financial analysis of integrated systems for the production of dairy heifers. Archivos de Zootecnia. 65, 203–212.

Stotzer, E. S., Lopes, L. B., Eckstein, C., **Carauta, M.**, Rodrigues, D. S., Bastianetto, E., 2014. Economic impact of parasitic disease in livestock. A Review. Revista Brasileira de Higiene e Sanidade Animal (*Brazilian Journal of Animal Hygiene and Health*). 8.

<u>Conference contributions</u>

Carauta, K., **Carauta, M.**, Reis, J. C., Isernhagen, I., 2014. Identificação de possíveis receitas de produtos florestais não Madereiros em projetos de restauração florestal no estado de Mato Grosso (*Identification of possible revenues from non-timber forest products in forest restoration projects in the state of Mato Grosso*), in . Anais do I Simpósio Brasileiro Florestal (*Proceedings of the 1st Brazilian Forestry Symposium*), Aquidauana, Brazil.

Carauta, K., **Carauta, M.**, Isernhagen, I., Dalfovo, W., 2016. Evaluation of forest restoration costs in degraded areas and Legal Reserves in Sinop, Brazil, in TROPENTAG, ed. Tropical and Subtropical Agricultural and Natural Resource Management, Vienna, Autria.

Carauta, M., 2013. Padronização de dados experimentais para avaliação econômica: a experiência da Embrapa Agrossilvipastoril (*Standardization of experimental data for economic evaluation: the experience of Embrapa Agrossilvipastoril*), in M. Pereira, G. Malafaia, L. Chiari, R. Almeida, E. Cardoso and T. Amaral, eds. Workshop em Avaliação Econômica de Projetos e Impactos de Tecnologia -WEIT (Workshop on Economic Evaluation of Technology Projects and Impacts), pp. 35–42.

Carauta, M., Chen, R., Carauta, K., Yonenaga, W., 2014. Impacto do câmbio na rentabilidade da produção de milho na região de Sorriso, MT (*Impact of the exchange rate on the profitability of maize production in the Sorriso, Mato Grosso state, Brazil*), in . Anais da 4ª Conferência em Gestão de Risco e Comercialização de Commodities (*Proceedings of the 4th Conference on Risk Management and Commodity Trading*), São Paulo, Brazil.

Carauta, M., Chen, R., Rossoni, A., Prado, W., Reis, J. C., Ferreira, D., 2014. Nova perspectiva de custo de produção na agropecuária: proposta de avaliação para sistemas de integração lavoura-pecuária-floresta - iLPF (*A new perspective of production cost in agriculture: proposal for evaluation crop-livestock-forestry*

integrated systems), in . Anais do XXI Congresso Brasileiro de Custos (*Proceedings of the XXI Brazilian Congress of Costs*), Natal, Brazil.

Carauta, M., Berger, T., 2016. Bio-economic simulation on bwUniCluster: The assessment of sustainable agricultural systems in Southern Amazon, Brazil, in S. Richling, M. Baumann and V. Heuveline, eds. Proceedings of the third Baden-Württemberg High Performance Computing Symposium (3rd bwHPC-Symposium). Heidelberg University Library heiBOOKS, pp. 81–82.

Carauta, M., Chen, R., Carauta, K., Yonenaga, W., 2015. Dynamic risk assessment model for corn production system in Mato Grosso, Brazil, in Proceedings of the 29th International Conference on Agricultural Economics. Milan, Italy.

Carauta, Marcelo, I. Guzman-Bustamante, K. Meurer, A. Hampf, C. Troost, R. Rodrigues, and T. Berger. 2018. Assessing the full distribution of greenhouse gas emissions from crop, livestock and commercial forestry plantations in Brazil's Southern Amazon. In Proceedings of the 30th International Conference on Agricultural Economics. Vancouver, Canada.

Carauta, M., Libera, A., Chen, R., Dantas, I., Hampf, A., Silveira, J. M., Berger, T., 2016. On-Farm trade-offs for optimal agricultural practices in Mato Grosso, Brazil, in Sociedade Brasileira de Economia, Administração e Sociologia Rural (SOBER), ed. 55º Congresso da SOBER.

Carauta, M., Libera, A. A. D., Latynskiy, E., Hampf, A., Silveira, José Maria F. J., Berger, T., 2016. Integrated assessment of novel two-season production systems in Mato Grosso, Brazil, in S. Sauvage, J. M. Sanchez-Perez and A. E. Rizzoli, eds. Proceedings of the 8th International Congress on Environmental Modelling and Software.

Farias, A., **Carauta, M.**, Reis, J. C., Pitta, R., Reis, C., 2011. Melhoramento genético de plantas em sistemas de integração lavoura pecuária floresta (Genetic improvement of plants in integratred agricultural systems), in F. Botelho and A. Baldoni, eds. Anais do 1º Simpósio de Melhoramento Genético de Plantas (*Proceedings of the 1st Symposium on Genetic Plant Breeding*), pp. 13–45.

Galbieri, R., Silva, J., Amus, G., Ribeiro, N., Vaz, C., Crestana, S., Torres, E., Salles, A., Farias, A., Faleiro, V., Lamas, F., Chitarra, L., Rodrigues, S., Matos, E., Spera, S., Magalhães, C., **Carauta, M.**, Zolin, C. A., 2013. Nematóides nos Sistemas de Produção de Algodão em Mato Grosso (*Nematodes in Cotton production systems in Mato Grosso, Brazil*), in . Anais do 9º Congresso Brasileiro de Algodão (*Proceedings of the 9th Brazilian Cotton Congress*), Brasília, Brazil.

Mössinger, J., **Carauta, M.**, Hilger, T., Berger, T., 2017. *Acrocomia* as accelerator for Integrated Agricultural Production Systems (IAPS) for family-based peasant systems in Paraguay, in B. Blochtein and G. W. Brun, eds. Book of abstracts of the 8th Brazil-Germany Symposium. Pontifical Catholic University of Rio Grande do Sul, Porto Alegre, Brazil.

Book chapters

Reis, J. C., **Carauta, M.**, Rodrigues, R., 2015. Agrosilvopastoral Systems in Brazil: An Agricultural Productive Strategy Based on Green Economy Concepts, in C. A. Zolin and R. Rodrigues, eds. Impact of Climate Change on Water Resources in Agriculture. CRC Press, pp. 85–100.