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Land Use Change, Agricultural Intensification and Low-Carbon Agricultural Practices in Mato Grosso, Brazil

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Executive summary

The process of land use change in Brazil has implications for food security, climate change and socioeconomic development at the local, regional and global levels. Largely driven by agricultural expansion over the past decades, such processes are likely to become even more pronounced in the coming years as Brazil is expected to satisfy a significant share of the global demand for food and energy.

In an effort to prevent further forest clearance and associated greenhouse gases (GHG) emissions, the Brazilian Federal Government has been promoting agricultural intensification through farming practices able to increase crop and livestock productivity while restoring degraded lands. Particular attention has been dedicated to the beef cattle sector in Mato Grosso state, a globally important center of agricultural production in Southern Amazonia, where some of the highest crop productivity levels contrast with pastures of low average stocking rates.

Two agricultural intensification strategies of growing importance in Mato Grosso are pasture to crop conversion (P2C) and integrated crop-livestock-forest systems (IS). While the first is a consequence of cropland expansion on pastures and might continue to happen through expected shifts in the relative profitability of certain commodities, the second entails the adoption of complex management practices and may be conditional on incentives and the existence of a favorable institutional context. Even though the Federal Government has already established policies and programs to promote P2C and IS and relies on both to reduce its total GHG emissions, the level of IS adoption remains low and many aspects of P2C and IS – including the drivers, barriers and impacts associated to their adoption – are poorly understood.

This thesis attempts to shed light on some of these uncertainties, so as to elucidate questions related to *where*, *how* and *why* P2C and IS happen. Using a combination of qualitative and quantitative research methods such as surveys, focus groups, remote sensing, spatial econometrics and agent-based modeling, it seeks a better understanding of the interplay between farmers' characteristics and preferences, supply chain infrastructure, market conditions and institutional factors, as well as how these may constrain or catalyze specific LUC pathways. Based on these findings, it ultimately compares the impacts of P2C and IS and concludes that the latter may offer greater benefits.

The first chapter (Introduction) contextualizes the research questions explored in the

subsequent chapters by offering an overview of land use change in Brazil and briefly reviewing the literature on agricultural intensification. The following chapters (2, 3, 4 and 5) form the core of the thesis and correspond to scientific publications developed during the Ph.D. program, all focused on the state of Mato Grosso. Results are analyzed in an integrated manner in the last chapter (Discussion & Conclusion) considering the broader implications of agricultural intensification through P2C and IS, leading to final policy recommendations.

Chapter 2 is dedicated to quantifying P2C and investigating its drivers. It reveals that: i) cattle vs. soy profitability and land prices do not fully explain P2C location; ii) land attributes on which classical agricultural development theories are based, may favor P2C but do not fully explain it; and iii) socioeconomic and institutional constraints are important in controlling pasture conversion, including non-productive sources of utility, producers' perception of contract enforcement, land markets and P2C-related transaction costs.

Chapters 3, 4 and 5 are dedicated to IS. Chapter 3 reveals the state-of-the-art of IS and how farmers perceive it, showing that: i) IS were concentrated in less than a third of the counties of Mato Grosso state – most of which were crop-livestock systems (iCL); ii) producers usually adopted one of three iCL strategies; and iii) the strategy choice was correlated with the land use transition undergone by each producer. Building on these findings, chapter 4 examines the determinants of wide-scale IS adoption and assesses the importance of household- and county-level variables, revealing that: i) adopters of iCL systems are better educated and have more access to technical assistance than specialized producers; ii) greater similarity exists between counties with iCL systems and soy-dominant vs. pasture-dominant counties; and iii) the presence of soy and pasture in a county is not a predictor of the occurrence of iCL systems. Finally, chapter 5 employs a bio-economic model that assesses how effective credit provision is in supporting the adoption of low-carbon systems – specifically IS and planted forests. The model simulates future land use changes in Mato Grosso under different credit scenarios and suggests that: i) credit has the potential to prompt greater adoption of IS; and ii) changes in the credit conditions (e.g. interest rates, down payment share and capital requirements) influence local and regional rates of IS adoption differently.

Most existing studies on land use change in Brazil are limited to the debate between intensification vs. extensification and tend to project the effects of intensification at an aggregate level, overlooking the different drivers and impacts of specific intensification pathways. By exploring the particularities of IS and P2C, this work offers evidence that these are

two distinct intensification strategies with widely different impacts – and, thus, should not be treated indistinguishably by policy makers. The merit of this thesis relies not only on its innovative theoretical approach, but also on its multidisciplinary and multi-scale nature. Through the mapping, measurement, description and interpretation of IS and P2C, it provides results able to inform policy making, facilitate the monitoring of existing policies and set the ground for subsequent research.

Zusammenfassung

Landnutzungsänderungen in Brasilien wirken sich auf Ernährungssicherheit, Klimawandel und soziökonomische Entwicklungen auf lokaler, regionaler und globaler Ebene aus. Da diese Landnutzungsänderungen hauptsächlich durch die Ausdehnung landwirtschaftlicher Flächen hervorgerufen warden, ist anzunehmen, dass sie sich in den nächsten Jahren noch verstärken warden, sofern Brasilien wie erwartet einen bedeutenden Anteil zur weltweiten Nahrungsmittel- und Energieproduktion beitragen wird.

Um weitere Waldrodungen und die damit verbundenen Treibhausgasemissionen zu verhindern, fördert die Brasilianische Bundesregierung eine landwirtschaftliche Intensivierung, die gleichzeitig die Produktivität pflanzlicher und tierischer Produktionsverfahren erhöhen als auch degradierte Flächen regenerieren soll. Besonders im Fokus steht hierbei die Rindermast im Bundesstaat Mato Grosso, einem weltweit bedeutenden landwirtschaftlichen Produktionszentrum im südlichen Amazonien. Während die dortige Pflanzenproduktion mit die höchste Produktivität aufweist, finden sich hier gleichzeitig eher niedrige Besatzdichten in der Tierhaltung.

Zwei landwirtschaftliche Intensivierungsstrategien mit zunehmender Bedeutung in Mato Grosso sind der Gründlandumbruch (pasture to crop conversion - P2C) sowie integrierte Produktionssysteme (Pflanzenproduktion – Viehaltung – Forstwirtschaft) (IS). Während erstere zumeist eine Folge der Ausweitung der Pflanzenproduktion auf Weideland ist, ausgelöst durch erwartete Änderungen in der srelativen Profitabilität der verschiedenen Produkte, bedarf letztere der Übernahme komplexer Produktionstechniken und möglicherweise staatlicher Anreize und günstiger institutioneller Rahmenbedingungen. Auch wenn die brasilianische Regierung zur Treibhausgasreduzierung bereits Förderprogramme für P2C und IS aufgelegt hat, ist die Übernahme integrierter Systeme weiterhin selten und viele Aspekte von P2C und IS wie Triebkräfte, Hindernisse und Auswirkungen sind noch nicht ausreichend verstanden.

Die vorliegende Arbeit versucht einige dieser Aspekte zu erhellen, indem sie der Frage nachgeht *wo*, *wie* und *warum* es zur Anwendung von P2C und IS kommt. Sie kombiniert qualitative und quantitative Analysemethoden wie Befragungen, Fokusgruppen, Fernerkundung, räumliche Ökonometrie und agentenbasierte Modellierung, um zu verstehen wie die Wechselwirkungen zwischen Eigenschaften und Präferenzen der Produzenten, der Infrastruktur

der Lieferkette, den Marktbedingungen und institutionellen Faktoren bestimmte Landnutzungspfade fördern oder behindern. Darauf basierend vergleicht es letztlich die Auswirkungen von P2C und IS und schlussfolgert das letztere die größeren Vorteile bietet.

Das erste Kapitel (Einführung) führt in den Kontext der Fragestellung ein und bietet einen Überblick über die Landnutzungsänderungen in Brasilien sowie die Literatur zur landwirtschaftlichen Intensivierung. Die folgenden Kapitel (2-5), der Hauptteil der Arbeit, entsprechen wissenschaftlichen Veröffentlichungen mit dem Fokus auf Mato Grosso, die im Rahmen des Promotionsstudiengangs erstellt wurden. Die Ergebnisse werden im letzten Kapitel (Diskussion und Schlussfolgerungen) zusammengeführt, welches die Folgen einer landwirtschaftlichen Intensivierung mittels P2C und IS erörtert und Vorschläge zur Politikgestaltung ableitet.

Kapitel 2 widmet sich der Quantifizierung des Weidelandumbruchs (P2C) und untersucht die zugrundeliegenden Antriebskräfte. Es zeigte sich, dass i) Profitabilitätsunterschiede zwischen Soja und Rindfleisch sowie Bodenpreise allein die räumliche Verteilung von P2C nicht vollständig erklären können; ii) Bodeneigenschaften, auf denen klassische landwirtschaftliche Entwicklungstheorien beruhen, begünstigen P2C, aber erklären ihn nicht vollständig, und iii) sozioökonomische und institutionelle Hürden spielen eine bedeutende Rolle, u.a. zusätzlicher, nicht-produktionsorientierter Nutzwert des Landes, Vertragsdisziplin, der Bodenmarkt und mit P2C verbundene Transaktionskosten.

Kapitel 3, 4 und 5 widmen sich integrierten Systemen (IS). Kapitel 3 behandelt den Stand der Technik im Bezug auf IS und wie er von den Produzenten wahrgenommen wird. Es zeigt sich, dass i) IS sich in weniger als einem Drittel der Gemeinden Mato Grossos finden und zu einem Großteil integrierte Pflanzenbau-Viehhaltungssysteme sind (iCL); ii) die Produzenten in der Regel eine von drei iCL-Strategien wählten; iii) die Wahl der Strategie mit der Landnutzungsentwicklung der einzelnen Produzenten korreliert. Darauf aufbauend untersucht Kapitel 4 die Bestimmungsgründe einer ausgedehnten Übernahme von IS auf Produzenten- und Gemeindeebene. Es zeigt sich, dass i) Nutzer von iCL-Systemen besser ausgebildet sind und besseren Zugang zu technischer Unterstützung als spezialisierte Produzenten haben; ii) Gemeinden mit iCL-Systemen mehr Gemeinsamkeiten mit Soja-dominierten als mit Weideland-dominierten Gemeinden aufweisen; und iii) die Präsenz von sowohl Soja- als auch Weideflächen in einer Gemeinde noch keine Vorhersage über die Präsenz von iCL in dieser Gemeinde erlaubt. Kapitel 5, schließlich, verwendet ein bioökonomisches Modell, dass untersucht wie effektiv die

Bereitstellung von Krediten zur Förderung von Low-Carbon Systems – besonders IS und Aufforstung ist. Das Modell simuliert zukünftige Landnutzungsänderungen in Mato Grosso unter verschiedenen Kreditszenarien. Die Ergebnisse deuten darauf hin, dass: i) Kreditvergabe zu einer stärkeren Übernahme von IS führen kann; ii) Veränderungen der Kreditkonditionen (u.a. Zinsen, Anzahlung, Kapitalbedarf) unterschiedlichen Einfluss auf locale und regionale Adoptionsraten von IS haben.

Die meisten vorhergehenden Studien, die sich mit Landnutzungsänderungen in Brasilien befasst haben, beschränkten sich auf eine Kontrastierung von Intensivierung und Extensivierung und projizierten Intensivierungsfolgen auf aggregierter Ebene. Sie übersehen dabei die unterschiedlichen Triebkräfte und Auswirkungen spezifischer Intensivierungsstrategien. Die vorliegende Arbeit jedoch liefert Belege dafür, dass die beiden hier untersuchten Intensivierungsstrategien P2C und IS stark divergierende Auswirkungen haben – und aus diesem Grund nicht undifferenziert behandelt werden sollten. Der Beitrag der Arbeit liegt hierbei nicht nur in ihrem innovativen theoretischen Ansatz, sondern auch in ihrer multidisziplinären und mehrskaligen Perspektive. Durch Kartierung, Messung, Beschreibung und Interpretation von IS und P2C, generiert sie die Voraussetzung für Politikgestaltung, Monitoring bestehender Programme und bereitet den Weg für weitere Forschungsarbeiten.

List of abbreviations

- ABC – Agricultura de Baixo Carbono [*Low-Carbon Agriculture*]
- ACRIMAT – Associação dos Criadores de Gado do Mato Grosso [*Mato Grosso's Association of Cattle Breeders and Ranchers*]
- AGRIANUAL - Anuário da Agricultura Brasileira [*Brazilian Agriculture Yearbook*]
- ANUALPEC – Anuário da Pecuária Brasileira [*Brazilian Livestock Yearbook*]
- APP – Area de Preservação Permanente [*Permanently Protected Areas*]
- APROSOJA – Associação dos Produtores de Soja do Mato Grosso [*Mato Grosso's Association of Soybean Producers*]
- AREFLORESTA – Associação de Reflorestadores do Mato Grosso [*Mato Grosso's Association of Reforestation*]
- BACEN – Banco Central do Brazil [*Central Bank of Brazil*]
- BMBF – Bundesministerium für Bildung und Forschung [*German Federal Ministry of Education and Research*]
- BNDES – Banco Nacional de Desenvolvimento [*Brazilian Development Bank*]
- BRL – Brazilian Real
- CarBioCial – Carbon Sequestration, Biodiversity and Social Structures in Southern Amazonia: Models and Implementation of Carbon-Optimized Land Management Strategies
- CAR – Cadastro Ambiental Rural [*Rural Environmental Registry*]
- CBC – "Coin-or branch and cut" solver
- CNA – Confederação Nacional da Agricultura [*Brazilian National Agriculture Confederation*]
- CONAB – Companhia Nacional de Abastecimento [*Brazilian National Supply Company*]
- COP – Conference of the Parties to the United Nations Framework Convention on Climate Change
- CPI - Climate Policy Initiative
- DAAD – Deutscher Akademischer Austauch Dienst [*German Academic Exchange Service*]
- EMATER - Empresa de Assistência Técnica e Extensão Rural [*Technical Assistance and Rural Extension Company*]
- EMBRAPA – Empresa Brasileira de Pesquisa Agropecuária [*Brazilian Agricultural Research Corporation*]
- FAO – Food and Agriculture Organization/ United Nations
- FASE – Federação de Órgãos para Assistência Social e Educacional [*Federation of Organizations for Social and Educational Assistance*]
- FSC – Food Security Center/ University of Hohenheim
- FGs – Focus Groups
- FRA – The Global Forest Resource Assessment
- GDP – Gross Domestic Product
- GEF – Global Environmental Facility
- GHG – Greenhouse Gases
- GM – Genetically Modified

- iCL – Integrated Crop-Livestock Systems
- iLF – Integrated Livestock-Forest Systems
- iCF – Integrated Crop-Forest System
- iCLF – Integrated Crop-Livestock-Forest systems
- IBGE – Instituto Brasileiro de Geografia e Estatistica [*Brazilian Institute of Geography and Statistics*]
- IIASA – International Institute for Applied Systems Analysis
- IMEA – Instituto Mato-Grossense de Economia Agropecuária [*Mato Grosso's Institute of Agricultural Economics*]
- INPE – Instituto Nacional de Pesquisas Espaciais [*Brazilian National Institute of Spatial Research*]
- IPAM – Instituto de Pesquisa Ambiental da Amazonia [*Amazon Environmental Research Institute*]
- IPCC – Intergovernmental Pannel on Climate Change
- IS – Integrated Systems
- ISA – Instituto SocioAmbiental [*Socioenvironmental Institute*]
- LUC – Land Use Change
- LULUCF – Land Use, Land Use Change and Forestry
- MANOVA - Multivariate Analysis of Variance
- MAPA – Ministério de Agricultura, Pecuária e Abastecimento [*Brazilian Ministry of Agriculture, Livestock and Supply*]
- MDA – Ministério de Desenvolvimento Agrário [*Brazilian Ministry of Agrarian Development*]
- MF – Ministério de Finanças [*Brazilian Ministry of Finance*]
- MONICA – Model for Nitrogen and Carbon in Agroecosystems
- MPMAS – Mathematical Programming Multi Agent-Based System
- MT – Mato Grosso state
- OLS – Ordinary Least Squares Regression
- ODD – Overview, Design Concepts and Details Modeling Protocol
- P2C – Pasture to Crop Conversion
- PAS – Plano Amazonia Sustentável [*Amazon Sustainable Plan*]
- PES – Payment for Environmental Services
- PNMC – Plano Nacional de Mudanças Climáticas [*Brazilian National Climate Action Plan*]
- PPCDAM – Plano Nacional de Prevenção e Controle do Desmatamento na Amazônia [*National Action Plan for Prevention and Control of Deforestation in the Amazon*]
- PROBIO – Projeto de Conservação e Utilização Sustentável da Diversidade Biológica Brasileira [*Project for Conservation and Sustainable Use of Brazilian Biological Diversity*]
- PRODES – Projeto de Monitoramento da Floresta Amazônica Brasileira por Satélite [*Project for Satellite Monitoring of the Brazilian Amazon Forest*]
- REDD+ - Reduced Emissions from Deforestation and Forest Degradation
- RL – Reserva Legal [*Legal Reserve*]
- RTSRS – Round Table on Responsible Soy

- SDC – Secretaria de Desenvolvimento Agropecuário e Cooperativismo [*Secretariat of Agricultural Development and Cooperativism/ Ministry of Agriculture*]
- SEAB – Secretaria de Agricultura e Abastecimento do Estado do Parana [*Department of Agriculture and Supply of the Parana State*]
- SENAR – Serviço Nacional de Aprendizagem Rural [*National Rural Learning Service*]
- SICREDI – Sistema de Crédito Cooperativo [*System of Cooperative Credit*]
- TNC – The Nature Conservancy - Brazil
- UFMT – Universidade Federal do Mato Grosso [*Mato Grosso Federal University*]
- UNFCCC – United Nations Framework Convention on Climate Change [*Convenção-Quadro das Naçoes Unidas para Mudanças Climáticas*]

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1. Introduction

Land use change (LUC) in Brazil is of profound importance for environmental quality, food security, and economic development both domestically and internationally. The pace and scale of LUC processes in the country have changed drastically over the past three decades as demographic, economic and technological transformations have altered patterns of demand for agricultural products. Such increase in demand led to an exponential expansion of farming and ranching areas, causing profound socioeconomic and environmental impacts where they occurred – among which massive forest clearance, biodiversity loss and the release of carbon into the atmosphere (Foley et al., 2005).

Projections that the world population will reach 9.1 billion by 2050 and the poor will increasingly converge on rich-country consumption patterns over that same period are expected to exacerbate LUC in the Brazil (World Bank, 2008; Ceddia et al., 2013). The country is expected to satisfy a significant share of the global demand for food and energy in the coming decades given that it concentrates most of the land available for agriculture and has some of the largest yield gaps in the world (IIASA-GAEZ, 2009; Nepstad et al., 2009; Godfray et al., 2010; Arvor et al., 2012). Although a combination of measures to increase efficiency of food production and utilization must be pursued, closing the gap between food demand and supply will require a substantial increase in food production compared to current levels (Royal Society, 2009; Tilman et al., 2012).

The transition between the Cerrado ecosystem and the Amazonia Rainforest, the two largest biomes of Brazil, is probably where the dispute between different land uses and the trade-off between cropland expansion versus preservation of primary vegetation have been most intense in the recent past. The large-scale colonization of the region began in the 1960s, largely due to subsidized credit given by the government to extensive ranching and to settlement and taxation policies which encouraged the establishment of property rights through occupation and productive use (Chaddad & Jank, 2006; Arvor et al., 2012). Population growth and the consequent expansion of both domestic and international consuming markets fed growth in the cattle industry in the following years and led to the consolidation of a beef supply chain in the region (Bowman et al., 2012). Almost in parallel, soy production too started receiving incentives (Garrett, 2013a; 2013b) and had its supply boosted by a number of factors – including technological improvements in seeds in the 1970s, the introduction of credit subsidies and price supports in the 1980s, market deregulation and tariff reduction in the 1990s, as well as high global prices for soy and a competitive Real/US Dollar exchange rate in the late 1990s and 2000s (Chaddad & Jank, 2006; Luna & Klein, 2006; Richards et al., 2012).

Large swaths of natural vegetation have been rapidly cleared as a consequence of the combined expansion of cattle and soya – currently, the two main agricultural commodities produced in Brazil for export markets. Land speculation, poorly defined property rights and a weak anti-deforestation monitoring system have traditionally made it possible – and often profitable – to clear new areas and leave behind degraded ones instead of engaging in long-term conservation measures (Fearnside, 2005; Nepstad et al., 2006; Barreto et al., 2013). Several studies have already highlighted the impact of soy and beef on deforestation, including the clear correlation between the spike in deforestation rates occurred in 2004 and an increase in soybean prices in the same year (Morton et al., 2006; Arima et al., 2011; Macedo et al., 2012). Even though soybean has expanded primarily on degraded pasturelands after 2006 (Brandão et al., 2005; Morton, 2012), it has also been hypothesized by different authors to function as an indirect driver of deforestation that displaces cattle ranchers into areas of native vegetation (Nepstad, 2006; Vera-Diaz et al., 2008; Wunder et al., 2008; Barona et al., 2010; Arima et al., 2011) and provides the impetus for new infrastructure projects in the region.

1.1. The recent decline of illegal deforestation in Brazil

Even though legal instruments and policies aimed at forest protection were already in place before the expansion of beef and soy, most of them had only been poorly enforced. In fact, for decades, the Brazilian government seemed to tolerate some deforestation on behalf of economic development and as a way to avoid conflicts with the rural lobby. At the end of 2004, Brazil was among the five largest emitters of greenhouse gases (GHG) worldwide, with agriculture and LULUCF respectively accounting for about 20% and 60% of its total emissions (UNFCCC 2014). The states of Pará, Rondônia and Mato Grosso showed the highest accumulated deforestation rates over the same period, and Mato Grosso alone had 135.000 square kilometers cleared between 1998 and 2008 (or 36% of all deforestation in the Amazon), with hotspots concentrated along the roads BR-158 and BR-163 (FRA 2009).

In response to these exorbitant figures and pressured by the international community, Brazilian authorities started to change their attitude towards illegal deforestation. The advancement of global negotiations on biodiversity protection and climate change, as well as sanctions imposed on Brazilian exports through blacklists created for municipalities with high deforestation rates, were also crucial for such change. Attention started being directed to three main policy efforts: the strengthening of command and control strategies; the extensive expansion of protected territories; and the adoption of conditional credit policies.

In 2005, the Brazilian Government established the "National Action Plan for Prevention and Control of Deforestation in the Amazon" (PPCDAM) in order to address key issues related to the forest protection. Those included agrarian and territorial organization, land use monitoring and control, fomentation of sustainable forestry activities, enhancement of coordination actions among different institutions, and the creation of protected areas and indigenous lands. In 2008, an even more ambitious initiative – the "Amazon Sustainable Plan" (PAS) – was launched with the financial support of developed countries to cut deforestation rates by 70% in 10 years, and to integrate other existing initiatives and programs (including the PPCDAM). At the 15th Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), Brazil announced a voluntary target for GHG emissions reduction of 36.1-38.9% of the total emissions projected by 2020. The target is part of the country's National Policy for Climate Change, enacted in December 2009 through the Presidential Decree n.7390/2010. Most of it (24.7%) shall be achieved through control and prevention of deforestation in the Cerrado and in the Amazon. The remaining should be achieved through sectoral plans on mitigation and adaptation to climate change, comprising the steel industry and the energy, transportation and agricultural sectors.

The plan for agriculture is officially entitled "Sectoral Plan for Mitigation and Adaptation to Climate Change Targeting the Consolidation of a Low Carbon Agriculture", but is better known as "ABC Plan". It is coordinated at the federal level by the Ministry of Agriculture, Livestock and Supply (MAPA) and jointly executed by the Ministries of Agrarian Development (MDA), Environment (MMA), Finance (MF), and the Brazilian Agricultural Research Corporation (EMBRAPA). Its main objectives are to prevent further deforestation and optimize land use by promoting measures that direct cropland expansion towards already deforested areas and intensify production sustainably. This should be achieved through capacity-building, research and technological development, technical assistance, and financing. The financing component of the ABC Plan constitutes a program in itself, the "ABC Credit Program", through which preferential loans are offered to farmers applying a so-called low-carbon agricultural practices.

These practices include: no-till farming; restoration of degraded areas; plantation of commercial forests; biological Nitrogen fixation; treatment of animal waste; and integrated crop-livestock-forestry systems (Government of Brazil, 2014).

After reaching more than 27,000 km2 in 2004, the annual deforestation rate in the Legal Amazon1 decreased almost continuously over the following years to about 4,500 km2 in 2012. Specialists attribute a minor part of the overall decline in deforestation to circumstantial factors such as periods of lower soy profitability (Nepstad, 2009; Macedo et al., 2012) but agree that structural factors played a major role – among which the above mentioned conservation policies (Assunção et al., 2012; DeFries et al. 2013), improved monitoring systems, improved law enforcement, supply chain interventions (such as fines and embargos) and the creation of new protected areas (Soares-Filho et al., 2010).

Whether this positive trend will hold in the long run is yet to be seen. A slight increase in deforestation rates was observed from 2012 to 2013 (INPE 2015), probably caused by land speculation and the effect of specific infrastructure works (IPAM, 2014). Small scale deforestation persists (Godar et al., 2014) and expected oscillations in the world's demand for agricultural commodities might have an impact on deforestation rates. Factors like rising soy and beef prices, lack of compliance with the Brazilian Forest Code and the devaluation of the local currency against the US Dollar have already contributed to worsen deforestation (Fearnside, 2015). As pointed out by Nepstad et al. (2014*), "the supply chain interventions that fed into this deceleration are precariously dependent on corporate risk management, and public policies have relied excessively on punitive measures. Systems for delivering positive incentives for farmers to forgo deforestation have been designed but not fully implemented. (…) The challenge now is to build upon this progress to construct a strategy for promoting a new model of rural development in which punitive measures are complemented by positive incentives and finance at scale for landholders, indigenous communities, counties, and states to make the transition to low deforestation, productive, sustainable rural development."*

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[1] The Legal Amazon is an administrative unit established by the Federal Law No. 5.173. It represents 59% of the Brazilian territory (5,016,136 Km^2) and encompasses all seven states of Northern Brazil (Acre, Amapá, Amazonas, Pará, Rondônia, Roraima and Tocantins) as well as parts of Mato Grosso and Maranhão. Three different biomes can be found within the Legal Amazon: the Amazon rainforest biome, 37% of the Cerrado (Savannas) and 40% of the Pantanal (flooded areas).

Although the persistence of low deforestation rates in the future is not absolutely certain, competition for land between different land uses has intensified in several regions, while total agricultural output growth increasingly relies on land use intensification (Hargrave & Kis-Katos, 2013; Nolte et al., 2013; Richards et al., 2014). Intensification and extensification are both ongoing processes that share several drivers and cannot be completely dissociated; for instance, novel crop varieties especially adapted to tropical conditions allowed the intensification of agricultural production while also facilitated the establishment and expansion of farm holdings in the region. Still, the transition from area expansion to productivity intensification as primary means to achieve greater agricultural outputs is a clear and undeniable trend in most of the country.

1.2. The Mato Grosso case study: from extensification to intensification

The state of Mato Grosso (Figure 1.1) is a globally important center for livestock and farming production (Brando et al., 2013). Located in Southern Amazonia on the so-called Arc of Deforestation, it is the third largest state in the country (903, 357 km2) and currently ranked first in the production of cattle meat, soybean, cotton and maize (CONAB, 2014). Besides having the largest soybean area in the country (8.6 million hectares in 2013/14) (CONAB, 2014), the state has also the largest herd (28 million animals) and pasture area (26 million ha) (IMEA, 2010).

Mato Grosso’s land use change trajectory was similar to that of Brazil as a whole. The state alone responded for 36% of all deforestation between 1998 and 2008 (Fearnside et al., 2009). Advances in tropical crop breeding, abundant land, lax land governance, several periods of high international soybean prices, and a weak national currency all contributed to a massive expansion of Mato Grosso’s cropland area (from 2.4 million hectares in 1990 to 11 million hectares in 2012) (Richards et al., 2012; Gasparri et al., 2013). Over the last years, however, changing economic conditions and stricter enforcement of the environmental legislation have caused agricultural intensification to become more important than extensification for agricultural production growth (Soares-Filho, 2006; Spera et al., 2014). After the peak of 2004/05, Mato Grosso saw its deforestation rate fall from 11,800 km2 in 2004 to 750 km2 by 2012 (INPE, 2015).

Figure 1.1 Mato Grosso state, Brazil

The land-use intensification pathways most widely adopted in Mato Grosso so far include increased yields in mechanized agriculture (Jasinski et al., 2005; Arvor et al., 2012; Garret et al., 2013), increased cropping frequency – particularly through double cropping (Arvor et al., 2012; Brown et al., 2012; VanWey et al., 2013; Spera et al., 2014) and cattle ranching intensification through improved pasture management, breeding and feeding (Euclides et al., 2010; Martha Jr. et al., 2012). Some of these pathways generate higher returns to labor (both in terms of amount of labor and/or specialized labor); some generate higher returns to capital (e.g. more inputs, incorporation of capital-intensive technologies, etc.); and others generate higher returns to labor and capital simultaneously. Two additional intensification pathways – the conversion of abandoned, unproductive pastures to cropland (Mann et al., 2014) and the integration of crop, livestock and/or forestry systems (Salton et al., 2014) – are becoming increasingly important in Mato Grosso as well, and will be the focus of this study.

1.2.1. **Pasture to crop conversion**

Most cropland expansion observed in Mato Grosso over 2001-2005 and 2006-2010 happened into previously cleared pastures (74% and 91%, respectively) (Macedo et al., 2012). Although the state is the main cattle producer in Brazil, most of its livestock production systems are highly land-intensive and have low average stocking rates (IMEA, 2010). Extensive ranching has persisted in regions where it is only marginally profitable to raise cattle (Nepstad et al., 2009; Bowman et al., 2012; Mann et al., 2014), but land is rapidly being reallocated to higher-value activities. The existence of approximately 25.7 million hectares of pastures in Mato Grosso, of which 2.2 million present some degree of degradation (IMEA, 2014), has been attracting investors interested in renting and/or buying land for crop cultivation. The sharp rise in land prices over the past five years, particularly pastures where logistics are favorable for the production of grains (FNP, 2014), may in part be a reflection of that. As Nepstad et al. (2014) points out, though beef production has a greater potential for yield increases compared with cropping systems and the realization of such potential could change the agricultural sector completely, soy continues to be the most profitable use of cleared lands in Mato Grosso state.

No specific targets were set for the dissemination of P2C in Brazil or in Mato Grosso. However, the Federal Government has sought to promote it in Northern Brazil as a whole claiming that it will spur economic development and reduce environmental impacts of agriculture. From the economic perspective, the argument is that, relative to cattle ranching, the cultivation of soy can promote regional development and improve Brazil's balance of payments thanks to its higher value and export orientation (Chaddad & Jank, 2006; Weinhold et al., 2013; VanWey, 2013). From the environment perspective, it is argued that guiding crop production onto degraded pastures will help restore soil fertility and spare land from deforestation.

Although P2C is not explicitly mentioned in the ABC Plan as eligible for ABC credit, rural producers may also make use of government loans by demonstrating that the shift from low input-ranching to high-output farming improves soil conditions (BACEN, 2015). Fertilizer applications, liming, and other field operations required by crop farming – which would hardly be undertaken by conventional ranchers – automatically contribute to the restoration of previously degraded pastures, at least in the short run (Oliveira et al., 2003; Volpe et al., 2008; Carvalho et al., 2010).

1.2.2. **Integrated systems**

The term "integrated system" has been used interchangeably with "mixed systems" or "agroforestry systems" in the literature and the definitions used by international organizations such as FAO, ICRAF and IFAD are somewhat discrepant. Still, they share common principles, including combining species deliberately, promoting diversity, as well as managing it so as to obtain higher productivity levels and/or specific products. Through these characteristics, IS mimic nature, thus favoring positive synergies that emerge from the interaction between crop, livestock and/or forest.

Integrated systems may differ depending on the way they are designed, both from a temporal perspective (whether it is sequential, rotational and dynamic) and from a spatial perspective (whether it is implemented at the plot, farm or landscape level). Ownership and management may be considered additional dimension of integration (Thornton & Herrero, 2015), but were not the focus of this study. Irrespective of these distinctions, every IS involves economic and agroecological interactions between their components, which should lead to improved use of resources, regeneration of degraded lands, among other benefits (Current et al., 1995; Nair, 2014).

The type of IS mostly practiced in the Brazilian Cerrado, which is how the term is employed in this work, is characterized by the combination of crop, livestock and/or forestry in the same area and over the same time period. This combination can be done according to rotation, succession or intercropping (Balbino et al., 2011). Low species diversity and intense field operations at a large scale are common in Mato Grosso. Although IS may include annual and/or perennial crops, different trees and several spatial arrangements, IS in the state usually involve soy and beef cattle only. Nevertheless, they can contribute to increase fertility and organic matter content in the soil, favoring biomass production and higher stocking rates in pastures (Bungenstab, 2012; Salton et al., 2013; Carvalho et al., 2014). Actually, the similarity between IS and conventional agricultural systems in terms of labor requirements and output levels favors IS expansion even in places where large-scale commercial agriculture is already in place. More labor-intensive agroforestry systems can be found in Mato Grosso, but their total area has remained small over the past decades (IBGE, 2006) in spite of its versatility and potential benefits.

In Mato Grosso, IS still occupy a very small area. According to official estimates based on PROBIO[2] data, the potential area for IS expansion in the state is greater than 6 million hectares,

[2] PROBIO (in Portuguese, "Projeto de Conservação e Utilização Sustentável da Diversidade Biológica Brasileira") is a project for the conservation and sustainable use of the Brazilian biological diversity for which land cover maps of all Brazilian biomes were generated. It is conducted by the Brazilian Ministry of Environment and co-funded by the Brazilian Federal Government, the Global Environmental Facility (GEF) and the World Bank.

but until 2010 only 90,000 hectares of IS could be found in the entire country (Balbino et al. 2011). However, IS are expected to expand significantly in the next years pushed by credit provision, the establishment of an Embrapa research unit exclusively dedicated to the topic, and other policy interventions. The Brazilian Government intends to promote the adoption of IS in additional 4 million hectares by 2020, which are expected to avoid the emission of 18-22 million tons of Carbon dioxide equivalent (CO2eq) into the atmosphere (or 0.7-0.8% of the country's total emissions in 2005) (Government of Brazil, 2014)[3].

1.3. Theoretical background

The challenge of increasing food production sustainably in Brazil has mobilized the scientific community around the question of whether agricultural intensification would be the right strategy to achieve it and how it should be promoted. Assuming that agricultural intensification refers to higher output produced per unit of land, "it may occur as a result of: a) an increase in the gross output in fixed proportions due to inputs expanding proportionately, without technological changes; b) a shift towards more valuable outputs; or c) technical progress that raises land productivity. In practice the intensification process may occur as a combination of these, but the relative feasibility of the three components is likely to vary greatly in different areas" (Carswell, 1997, pp. 3).

A number of studies published over the past years have tried to explore pros and cons of intensification as opposed to agricultural expansion and/or predict or prescribe the rate at which intensification is to occur in the future in Brazil. However, several aspects of the debate remain disputed and are often ignored by methodological approaches of limited scope that often yield discrepant results and policy recommendations.

From an environmental perspective, many studies highlight the benefits that may arise from agricultural intensification in terms of land-sparing and GHG emissions reduction (Burney et al., 2010; Omer et al., 2010; Tilman et al., 2012). However, it has already been shown that extremely intensified farming systems may lead to Nitrogen pollution (Galloway et al. 2008, Smith 2013), problems in watersheds (O'Neill et al. 2013) and biodiversity decline (Phalan et al., 2011; Tscharntke et al., 2012). From a socio-economic perspective too, positive impacts of

[3] This calculation considered that IS would, in average, sequester 1,83 Mg CO_2eq per hectare per year (Government of Brazil, 2011).

agricultural intensification are often elicited (VanWey et al., 2013; Weinhold et al., 2013) but the broad range of stakeholders that exist in the Brazilian land use context tends to be overlooked. Such diversity of profiles and interests constitutes an additional source of complexity when dealing with allocation of land to different uses, especially concerning the many livelihoods in which forests play a critical role (Fearnside, 2009). Besides, as already shown by Lapola et al. (2013), agricultural intensification may displace smallholders who can no longer compete with large-scale enterprises and *"reinforce the long-established inequality in land ownership, contributing to rural-urban migration that ultimately fuels haphazard expansion of urban areas".*

No agreement exists either with regards to the role of intensification in minimizing cropland expansion and slowing deforestation in Brazil. Cattaneo (2005) examines how recent trends in agricultural productivity in Brazil have affected deforestation and agricultural incomes using a general equilibrium model. Results show that innovation rates for livestock activities inside the Amazon contributes to increasing agricultural income in the region, but with greater deforestation rates, while innovation in livestock outside the Amazon leads to lower deforestation rates, but also lower agricultural incomes overall (both within and outside the Amazon). Martha Jr. et al. (2012) show empirical evidence that, over the 1950-2006, productivity gains explained 79% of the growth in beef production in Brazil and supported a land-saving effect of 525 million hectares. Strassburg et al. (2014) show that improving the use of agricultural lands could meet production demands and spare natural habitats in Brazil.

Still concerning the impacts of intensification in terms of land sparing, Byerlee et al. (2014) argues that this depends on whether the intensification process is technology- vs. market-driven, as well as where it happens (i.e. away from the agricultural frontier, on the frontier, or if it is broadly distributed across space). The same study also lists a number of market effects that mediate this process, including spatial shifts in production, the impact of labor markets, and the existence of more efficient innovation regions. Alcott (2005) and Hertel (2013) have showed that the Jevon's Paradox may apply when, at the local level, intensification raises profitability and returns to land – two phenomena already observed in Mato Grosso (Miao, 2014; Mann. 2014).

The intensification of beef cattle production systems, in particular, has been the main focus of several recent studies concerned GHG emissions in Brazil. Most of these studies use IAMs to investigate the effect of specific interventions at the national and/or global scale. The agricultural productivity function embedded in the models usually allows for substitutability among production factors (e.g. land, labor, capital), but a few models theorize it differently, so as to treat materials and energy separately. Future deforestation is mostly projected based on historical trends, whereas cropland expansion is simulated according to population growth and changes in demand. For instance, Gouvello et al. (2010a; 2010b) state that the combination of improved forage and genetically superior bulls, combined with increase in livestock productivity, would reduce direct livestock emissions from 273Mt to 240Mt CO2 per year in 2030 (comparable to 2008 emissions levels). Lapola et al. (2010) use a spatially explicit model to project LUC caused by the expansion of biofuel plantations in Brazil in 2020 and show, among other results, that an increase of 0.13 head per hectare in the average livestock density throughout the country could avoid the indirect LUC caused by biofuels, even assuming soybean as the biodiesel feedstock. Bustamante et al. (2012) estimate emissions from three major GHG sources associated with cattle raising in Brazil over 2003-08, concluding that "concerted action it is possible to promote both the rehabilitation of degraded land and the spatial intensification of livestock activities, with higher land productivity". Gerber et al. (2013) published a global assessment of emissions and mitigation opportunities in the livestock sector and showed through case studies that animal and herd efficiency improvements in Brazil could reduce grazing land use and associated LUC emissions by up to 25% of the country's current emission levels. Finally, Cohn et al. (2014) apply a partial equilibrium model of global land use to show that policies to encourage cattle ranching intensification in Brazil could cost-effectively abate GHGs by sparing land and limiting deforestation.

Although major differences in the results of these studies can be explained by the way factors like trade, trading regions, and consumption elasticity are defined, they seem to agree that the Brazilian cattle sector is where the largest potential for climate change mitigation resides. Still, none of them considers the broader socioeconomic and environmental consequences that may arise, how different households may be affected, or whether local and global impacts are the same. Each analytical approach and technique has advantages and disadvantages, and factors such as the research motivation and data availability are certainly relevant for the selection of a specific approach/technique.

1.4. Study's motivation and research questions

The existing literature on land use change in Brazil has drawn a lot of attention to the current productivity gap in the Brazilian cattle sector and also offered first estimates of what could be achieved in terms of food production and GHG emissions. However, most studies have discussed intensification from a limited perspective, neglecting that agricultural intensification and land use change are characterized by institutional complexity, linkages and interactions across multiple scales hardly captured by a single research method. Although intensification is generally treated as a single process, the technology through which it occurs, the associated management practices and the stakeholders involved may characterize distinct LUC pathways in reality. The same intensification process is bound to have different effects depending on site-specific conditions and/or the broader macro-economic and institutional contexts.

The Brazilian Government has been advocating intensification as a promising strategy to develop a more efficient and environmentally sound agriculture in Mato Grosso, particularly given the state's great agricultural potential and crucial geographic location for the protection of the Amazon rainforest. Yet, little is known about the drivers and constraints or advantages and disadvantages of intensification processes in Mato Grosso. P2C and IS might decrease pressure on deforestation provided that agriculture intensification leads to less land used elsewhere through a price effect (Cohn et al., 2011; Strassburg et al., 2014) or even increase pressure on deforestation through an income effect (particularly if effective conservation policies are not yet in place) (Rudel et al., 2009; Angelsen, 2010). The promotion of local economic development, on the other hand, could happen through the improvement of the balance of payments thanks to the higher value and export orientation of soybeans over the beef, but could also affect small and large producers differently. The fact that Mato Grosso is a large and dynamic state with sub-regions and characteristics similar to both agricultural frontier regions and established agricultural centers adds complexity to the problem and requires a more nuanced view of each intensification process. The same is true about the new context of relative land scarcity in Brazil, as land use changes may involve land transactions between different agents.

The successful implementation of policies aimed at promoting agricultural intensification where it may be advantageous also requires a deep understanding of the drivers and barriers to LUC and the interplay between them at the local and regional scales. The absence of P2C where cattle ranching is less profitable than farming and the low rate of IS adoption by farmers in Mato Grosso despite the incentives offered through the ABC credit (Observatório ABC, 2013) are evidence of the need to investigate what influences land conversion. Traditional agricultural development theories exclusively focused on land attributes might explain some of the elements involved in farmers' land use choices in Mato Grosso (Spera et al., 2014), but fail to capture micro-level factors and unobservables which are increasingly important with regards to LUC decisions. Moreover, no official statistics on P2C or IS are available despite the importance of these processes and the fact that targets for the diffusion of the latter exist and must be monitored. Basic knowledge gaps exist concerning the current extent of P2C and IS, where within MT each of these processes is located, how they have been operating in practice and what challenges are associated to their dissemination.

This thesis constitutes a first step towards a deeper understanding of recent land use change and agricultural intensification in Mato Grosso by examining two intensification pathways of growing importance in the state: pasture to crop conversion (P2C) and integrated systems (IS). Despite the many different concepts of intensification found in the literature (Carswell, 1997; Hussein & Nelson, 1999; Smith, 2013), the thesis employs the definition used in classical economic theory of *"increase in the productivity of land measured by the real value of agricultural output per hectare"* (Hayami & Rutan 1971). The work builds upon the understanding that agricultural intensification is not the same process in every context and that different intensification processes or mechanisms have distinct socioeconomic and environmental impacts. Based on these findings, bioeconomic simulations are conducted to assess the cost-effectiveness of credit provision on the adoption of integrated systems under different policy scenarios.

Acknowledging that different research methods are complementary and equally important to inform policy at various decision-making instances, the thesis explore P2C and IS through a combination of qualitative and quantitative research methods from land change science and farm economics. Remote sensing, surveys, focus groups and spatial econometrics are some of the tools applied to look into characteristics of producers and their farms, socioeconomic and/or institutional factors, risk perception, cultural preferences, supply chain infrastructure and market conditions that may constrain or catalyze land use change. The interplay between these factors and the determinants of agricultural technology adoption is also considered here given that "people's responses to economic opportunities, as mediated by institutional factors, drive land cover change worldwide" (Lambin et al., 2011). The insights gained throughout the research inform the parameterization and calibration of the bioeconomic simulation modelling in Mato Grosso.

1.5. Thesis outline

This thesis is structured upon three chapters that correspond to scientific publications developed during the Ph.D. program. It also includes a final chapter of general discussion and conclusions, as detailed below.

Chapter 2 ("Socioeconomic and biophysical dimensions of pasture to crop conversion in Brazil") introduces the topic of land use change and agricultural intensification by presenting a study on cropland fluxes and pasture to crop conversion in Mato Grosso state. It draws on quantitative and qualitative research with a broad range of agricultural sector informants to better characterize factors influencing P2C the establishment of P2C contracts. More specifically, it looks into the influence of land attributes, farm and farmer characteristics, and land institutions (particularly land markets) on the occurrence of P2C in the state.

Chapter 3 ("Adoption and development of integrated crop-livestock-forestry systems in Mato Grosso, Brazil") presents the state of the art of integrated systems. Besides mapping and describing pioneer initiatives, this chapter assesses how farmers perceive this new technology and identifies IS adoption determinants. The analysis uses results of a survey conducted in situ in 2012/13 focused on the comparison of farmers' socio-economic profiles and the characteristics of farming systems related to all main aspects of the study (including the different IS strategies found in the state, farms characteristics, farmer technological profile, legal status of the rural property, production data, challenges of IS implementation, farmer exposure to information, financing, among others). At the end, the chapter discusses policy implications of these results and whether any of the factors mentioned above represents a barrier to a broader IS diffusion.

Chapter 4 ("The wide-scale adoption of integrated crop-livestock systems in Mato Grosso, Brazil: Evidence from the household and regional levels") presents a subsequent study on the wide-scale dissemination of integrated crop-livestock systems (iCL), the most common type of IS in Mato Grosso. It investigates the factors that may influence this process by examining the decision-making process faced by local farmers for the adoption of management innovations and at the same time the spatial correlation between iCL occurrence and biophysical, socioeconomic, and institutional characteristics of each state county.

Chapter 5 ("Can preferential credit programs speed up the adoption of low-carbon agricultural systems in Mato Grosso, Brazil? Results from bioeconomic microsimulation") employs a bioeconomic model parameterized according to five municipalities in Mato Grosso to assesses the effectiveness of the ABC credit program for the adoption of IS and planted forests.

The model simulates future land use changes in Mato Grosso under different credit scenarios and offers detailed quantitative evidence of the influence that varying credit parameters (e.g. interest rates, down payment share and capital requirements) may have on technology adoption.

Chapter 6 ("Discussion & Conclusions") discusses all results together by further exploring the parallels and contrasts between P2C and IS, as well as the links between the object of this study with global food security. Although some of the ideas introduced in earlier chapters already reveal important aspects of the inherent interdependence among land use change, agricultural intensification, low-carbon agricultural practices and food security, this part of the thesis highlights that intensification alone does not always ensure sustainability. In light of the findings of this work, we discuss the drivers and constraints of P2C and IS as well as whether agricultural intensification through each of these practices might help ensure the world's growing food demand while reducing the pressure for deforestation and the GHG emissions at the state levels. The thesis concludes with a brief panorama of what has been presented, the discussion of strengths and weaknesses of the study, additional policy recommendations and a list of future research avenues for the consolidation of low-carbon agricultural systems in the region.

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2. Patterns and processes of pasture to crop conversion in Brazil

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Abstract

The rate and location of cropland expansion onto cattle pastures in Brazil could affect global food security, climate change, and economic growth. We combined mapping, statistical modeling, and qualitative methods to investigate patterns and processes of pasture to crop conversion (P2C) in Mato Grosso State (MT), Brazil, a globally important center of agricultural production. P2C constituted 49% of cropland expansion from 2000 to 2013. For a random sample of MT, we estimated a regression model skilled at predicting P2C in the rest of the state as a function of cattle ranching suitability, cropping suitability, and P2C conversion costs. Surprisingly, just 1/7 of pasture agronomically suitable for cultivation had undergone P2C. Hedonic regressions revealed that agronomic characteristics of land were associated with less than 20% of the variation in cropland suitability. Instead, the majority of the variation stemmed from a combination of proximity to agricultural infrastructure, characteristics of neighboring lands, and time fixed effects. The weak relationship between agronomic characteristics of land and P2C suggests a less certain future for P2C than projections made with agronomic models. Consequentially, complications may arise for greenhouse gas mitigation policies in Brazil predicated on widespread expansion of P2C instead of cropland expansion into natural areas. We conducted follow-up qualitative research showing that because P2C has often involved land rentals or sales and that thus poorly functioning land institutions may constrain P2C. Locally poor land quality, omitted from agronomic P2C predictions, can either catalyze or constrain P2C by limiting returns to ranching, farming, or both. Interventions to control rates and locations of P2C should take these insights into account.

2.1. Introduction

Expansion of agricultural areas and more recently agricultural intensification have transformed Mato Grosso, Brazil (MT) into a globally important center of agricultural production (Brando et al., 2013). Advances in tropical crop breeding, abundant land, lax land governance, several periods of high international soybean prices, and a weak national currency, all helped prompt the value of agriculture production in MT to increase roughly fivefold from 1990 to 2013 (Chaddad & Jank, 2006; Richards et al., 2012; IBGE, 2013; Nepstad et al., 2014).

Increases in production in MT stem from agricultural intensification and extensification, two ongoing processes that have both shared and distinct drivers. For example, novel crop varieties adapted to tropical conditions have enabled intensification of agricultural production and facilitated the establishment and expansion of farm holdings in the region (Chaddad & Jank, 2006). In recent years, changing land prices, anti-deforestation policies, and a scarcity of remaining high quality land have combined to cause agricultural intensification to comprise an increasing share of production growth relative to agricultural extensification (Soares-Filho et al., 2006; Hargrave & Kis-Katos, 2013; Nolte et al., 2013; Spera et al., 2014).

Pathways of agricultural intensification observed in MT include increased cropping frequency, increased yields in mechanized agriculture, cattle ranching intensification, integration of crop and livestock systems, and – the focus of this paper – conversion of cattle pastures to cropland (P2C). P2C may involve not only the landholder, but also a renter or potential buyer. It can happen through “self-conversion” (where a rancher undertakes the conversion herself); “renting” (a rancher rents all or part of his land to a farmer); and “selling” (a rancher sells all or part of her land to a farmer). P2C is conducted on entire farms or parts of them and can be reversed in response to changing conditions.

Typically, the value of production per hectare of crop farming in Northern Brazil is greater than the value of cattle ranching production (Richards et al., 2014). Thus, relative to cattle ranching, crop farming might promote regional economic development (VanWey et al., 2013). The higher value and heightened export orientation of soybeans vs. beef could also increase the value of Brazil's exports (Chaddad & Jank, 2006; VanWey et al., 2013; Weinhold et al., 2013). Agricultural expansion onto low-productivity pastures, might also help to restore soil fertility, impel neighboring pastures into more intensive cultivation, and spare land from deforestation (Gil et al., 2015). Critics have argued that P2C does not necessarily ensure economic development, that large-scale crop farming may foster local environmental degradation and social pressure, and that the effect of P2C on deforestation rates through land sparing is ambiguous.

P2C might indeed decrease deforestation provided that agriculture intensification leads to less agricultural land used elsewhere through an agricultural commodity price effect (Cohn et al., 2014). More P2C, however, might also increase deforestation through a farmer income effect – particularly if effective forest protection policies are not in place (Rudel et al., 2009; Angelsen, 2010).

Nevertheless, P2C is projected to deliver 10% - 90% of the GHG emission reduction target defined under Brazil's National Climate Action Plan (PNMC) (Cohn et al., 2011). For its potential contribution to climate change mitigation, P2C conversion is also eligible for preferential loans under programs of Brazil's "Low-Carbon Agricultural Plan." Of the six loan categories in the plan, four are designated for activities associated with elements of P2C: nitrogen fixation, restoration of degraded pastures, low-tillage agriculture, and integrated crop, livestock, and/or forestry systems (Government of Brazil, 2014).

Several recent studies find enormous agronomic potential for P2C across Brazil, including MT (da Silva, 2014; Alkimim et al., 2015; Gibbs et al., 2015; Graesser et al., 2015; Martini et al., 2015). One study finds that of MT's 25 million hectares of cattle pasture, 11 million hectares have the potential to be converted to cropland (da Silva, 2014). If all pasture area classified as suitable was converted, the cropping area in MT would more than double. Another study suggests that as many as 13 million hectares of additional soy expansion could occur in MT on non-natively vegetated lands, a substantial share of which are likely pasture (Gibbs et al., 2015).

Given the large expanse of pasture suitable for P2C and the continued expansion of agriculture on non-pasture land, we hypothesize cropland expansion on pasture in MT to be influenced not only by agronomic factors, but also a combination of social, institutional, and economic factors. We adopted a mixed methods approach to investigate these constraints and their impacts on the geography of P2C conversion.

Our research entailed four complementary data collection activities—a comparison of satellite maps of land use, a statistical analysis of the likelihood of pasture to crop conversion, cattle rancher and crop farmer focus groups, and qualitative interviews with agricultural experts. First, we assembled the most complete mapping of P2C in Mato Grosso. This mapping reveals the amount of P2C, whether it has persisted as cropland, and how P2C areas compare to the rest of cattle pasture and cropland.

We next investigated the geographic drivers of the spatial patterns of P2C mapped. We adapted a statistical approach detailed in (Irwin & Geoghegan, 2001) in which the decision to maintain cattle pasture or convert it to mechanized cropland is a discrete choice where each pixel is expected to have the profit maximizing land use, given a set of agronomic characteristics, centrality with respect to cities and agricultural infrastructure, the characteristics of neighboring pixels, and whether the pixel is found in a protected area. We examined the sensitivity of model results to controls for pasture to crop conversion costs, investigated the predictive skill of the estimated model, and mapped the likelihood that remaining pastures in MT would be converted to cropland.

The large and heterogeneous influence of variables not easily represented in this type of model, such as land institutions and rural producer characteristics, are likely to lead to discrepancies between observed P2C and the P2C likelihood modeled. Thus, in parallel, to further elucidate P2C mechanisms and patterns, we undertook farmer focus groups and semi-structured interviews with agricultural experts. To meaningfully reconcile these qualitative approaches with the statistical analysis, we address three additional research questions devised to enable synthesis of results across methods: How do expert interviews differ from FGs in portraying the drivers and constraints of P2C? What are the characteristics of P2C at the municipality level in focus groups vs. the statistical analysis? What do the statistical vs. qualitative methods reveal about the Northeastern P2C hotspot?

2.2. Material and methods

Our research sought to synthesize complementary quantitative and qualitative approaches to investigate the determinants of, and the potential for, P2C in Mato Grosso, Brazil. For some variables, we obtained results from multiple methods, enabling cross-comparison and assessment of the level of agreement or disagreement. Table 2.1 shows the variables on which each method focuses. Research for the paper was conducted over the period March 2014 to September 2014 by the authors and by agricultural consultants trained by the authors.

Table 2.1. Groups of variables for which each research method offers insights.

	Agronomic suitability	Logistics & centrality	Land institutions	Farm & farmer characteristics	Neighboring areas	Protected areas
Satellite imagery		✓			✓	✓
Statistical analysis	✓	✓			✓	✓
Focus groups	✓	✓	✓	✓	✓	
Expert interviews	✓	✓	✓	✓	✓	

2.2.1. **P2C mapping**

We developed a land use dataset containing annual thematic land use maps for Mato Grosso State over the period growing year 2000 to 2001 (2000/01) to 2012/13. The dataset contains cattle pasture areas ("Past") for the years 2000/01 to 2003/2004, 2007/2008, and 2009/10; and mechanized cropland areas ("Crop") for the years 2001/02 to 2010/11 and 2012/13. We used ArcMap 10.2 to harmonize the projection and pixel size of the cropland and pastureland maps, exported them as ASCIIs, imported the ASCIIs into Stata, and created a Stata dataset containing one observation for each 250m pixel-year (n=16,007,297, t=13). We used Stata to generate a new variable indicating pixels classified as cropland in year *t* and classified as pasture during one or more years during the period *t*-1 to 2000/01 ("P2C").

The pasture data merges three datasets. The first was released in 2002 as part of PROBIO, an effort organized by the Brazilian government to perform supervised classification of all land use and land cover in the country present in the year 2000/2001 (Sano et al., 2010). The second dataset was released in 2006 as part of a mapping of land use and land cover in Mato Grosso. It tracks and classifies the fate of government reported deforested lands in Mato Grosso over the 2001 to 2004 period (Morton et al., 2006). The third dataset, Terraclass, tracks the fate of all government-reported deforestation between 1998 and 2010 (de Almeida et al., 2009). The pasture in the second dataset (Morton et al., 2006) is not a subset of pasture in the third dataset (Terraclass) because it includes pixels that were pasture during the 2001 to 2004 period but might not have remained pasture long enough to be captured in Terraclass. Meanwhile, Terraclass may include pixels deforested during the period 2001 to 2004, but that were not converted to pasture until after 2005.[4] Our analysis does not include pasture that was converted

[4] The combined area of pasture pixels in Morton et al. and Terraclass is much smaller than the area classified as

from the non-forested regions of the state after 2002 because no mapping of these pastures has been conducted. Still, our study is the first detailed analysis of P2C in Mato Grosso, encompassing, to our knowledge, all locally-focused spatially explicit pasture datasets. Table 2.2 summarizes all data sources used for P2C mapping and the abbreviations of land use classes as mentioned throughout this paper.

Table 2.2. Description of land use categories and land use datasets.

Land Dataset	Variable Code	Year(s)	Derivation	Source
Probio pasture	n.a.	2001	Land Classified as Pasture as part of Land Classification for Brazil in the year 2002	Sano et al., 2010
Morton pasture	n.a.	2001 to 2004	The subset of PRODES deforestation over the period 2000 to 2004 classified as pasture	Morton et al., 2006
Terraclass pasture	n.a.	2008, 2010	The subset of PRODES deforestation over the period 1998 to 2010 classified as pasture in either 2008 or 2010.	de Almeida et al., 2009
Pasture	Past	2001 to 2012	The union of all previously identified pasture from Probio, Morton and Terraclass	n.a.
Mechanized cropland	Crop	2001 to 2013	Satellite derived map of all mechanized agriculture in each growing season in MT over the period 2000/01 to 2012/13	Spera et al., 2014
Cropland expansion on pastures	P2C	2002 to 2013	In a given year, the intersection of mechanized cropland and areas previously classified as pasture	n.a.

The crop agriculture dataset we used is derived from satellite images of Mato Grosso collected over the period 2000/01 to 2012/13 (Spera et al., 2014). The approach maps area of soy, maize and cotton. Together, these correspond to more than 90% of the total cropland in the state (IBGE, 2013). The mapping was based on an algorithmic classification of land uses derived from 8-day MODIS Enhanced Vegetation Index values during the state's agricultural growing season. The initial classification was then validated using expert classification of randomly selected points in Landsat images and roughly 7,000 randomly sampled field validation points.

pasture/cerrado by Macedo, M.N., DeFries, R.S., Morton, D.C., Stickler, C.M., Galford, G.L., Shimabukuro, Y.E., 2012. Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. Proceedings of the National Academy of Sciences 109, 1341-1346. In Macedo et al. study, pasture/cerrado areas are all the remaining PRODES deforestation pixels that could not be classified as forest or cropland. The Cerrado Biome and the Amazon Biome are administrative units relevant for Brazilian land use policies. They do not designate homogeneous vegetation. Thus, "cerrado" is not the same as the Cerrado Biome (a vast tropical savanna ecoregion). The pasture area captured in our analysis is primarily found on lands that were formerly dense tropical forest. It is exclusively these lands that are monitored for deforestation by the Brazilian government. The Cerrado Biome comprises 40% of MT and the Amazon Biome comprises 53% of MT.

The method is described in detail in Spera et al. (2014) and yields similar results to a number of other studies that map cropland in Mato Grosso using satellite remote sensing (Jasinski et al., 2005; Morton et al., 2005; Arvor et al., 2012; Macedo et al., 2012; Brown et al., 2013; Spera et al., 2014).

2.2.2. Statistical analysis of likelihood of pasture to crop conversion

Rent models derived from agricultural census data at the level of municipalities have been used analyze the coarse geography of agricultural expansion in Brazil (Pfaff, 1999; Chomitz & Thomas, 2003). Mann et al. (2014) statistically analyzed pixel-level pasture and cropland rents and used the analysis to explore the determinants of cropland and pastureland in the state. But, none of the previous works (1) used conversion likelihood derived from land price observations (2) investigated the specific determinants of the likelihood of pasture to crop conversion as opposed to the likelihood of all cropland expansion or all pasture and (3) performed the analysis on so comprehensive a dataset.

As P2C is both a form of land use change (LUC) and a case of land use intensification our research draws on both Land Change Science and agricultural economics. Both LUC and agricultural intensification result from many interacting processes which operate over a range of scales in space and time and which are driven by biophysical and socioeconomic dynamics and by heterogeneous producers (Lambin et al., 2001; Turner et al., 2007; Martínez et al., 2011). Both phenomena can be modeled as discrete choice problems. Therein, the most likely land use or the most likely observed agricultural technology is the one for which the stream of future returns to the land user, less the cost of land conversion/uptake exceeds all alternatives future return streams (Feder et al., 1985; Irwin & Geoghegan, 2001).

The streams of future returns associated with agricultural activities may be proxied in a number of ways. One basic distinction is the bottom up approach that incorporates costs and benefits of multiple systems of production (or their proxies) vs. a top down approach that incorporates data or proxy data on producer profits from multiple systems of production. Based on data availability we adopted a version of the latter approach (Bockstael, 1996).

We modeled the decision to maintain cattle pasture or convert cattle pasture to cropland (that is, engage in P2C) on each pixel in our analysis as a discrete choice problem of land conversion where landholders seek to maximize profit. We adapted an approach detailed in Irwin & Geoghegan (2001) and based upon the theoretical assumption shown in equation (1).

Therein, the initial conversion from pasture, *p*, to cropland, *c*, can be expected in location *j* and time *t* if the present value of the future stream of returns, *W*, from cropland less the cost of first time conversion of the pixel, *C*, from pasture to cropland is greater than the present value of the future stream of returns from pasture or any other land use, *m*, minus the associated conversion costs.

(1) $W_{jct|p}$-$C_{jct|p} > W_{jmt|p} - C_{jmt|p}$

Since some elements of both returns and conversion costs are unobservable, we rewrote (1) as a statement of probability, allowing for both patterned and random portions of returns and conversion costs. We used proxies for conversion costs and returns given that we did not directly observe them. For conversion costs, we used an estimate of the cost of transporting lime to each pixel from the closest of the two major sources of lime in Mato Grosso. Together, these sources account for over 95% of all lime used in Mato Grosso (ABRACAL, 2014). We proxied returns to ranching and farming using location-specific estimates of the land prices for cattle pasture and cropland respectively. The rationale, described by Bockstael (1996), is that the price of a given parcel of land in a particular use can be expected to be proportional to the bid rent in that use. The bid rent is the maximum land rent that a land user can be expected to be willing to pay for a particular parcel in a particular land use state.

Land prices observations collected by the agricultural consulting company FNP were available as a balanced panel for years 2002 to 2010 for a subset of the state of Mato Grosso (n=44/141 municipalities for pasture, and n=38/141 municipalities for cropland) (Richards et al., 2014). We employed a hedonic approach in which we statistically modeled the FNP pasture price (2) and the FNP cropland prices (3) as functions of variables representing agronomic suitability, centrality with respect to cities and agricultural infrastructure, protected areas, and year fixed effects. We estimated model (2) over the subset of each municipality, *i*, that was pasture in year *t* and estimated model (3) over the subset of *i* that was cropland in year *t*. In this way, cross sectional independent variables have different values each year, owing to the changing footprint of pasture and cropland over time.

(2) $PastPrice_{it} = \alpha_0 + \boldsymbol{\alpha_1 Agronomic_{it}} + \boldsymbol{\alpha_2 PastCentrality_{it}} + \boldsymbol{\alpha_3 Protected_{it}} + W_t + \varepsilon_{it}$

(3) $CropPrice_{it} = \beta_0 + \boldsymbol{\beta_1 Agronomic_{it}} + \boldsymbol{\beta_2 CropCentrality_{it}} + \boldsymbol{\beta_3 Protected_{it}} + W_t + \varepsilon_{it}$

Regressions (4) and (5) are identical to (2) and (3) except they also control for bias stemming from the characteristics of neighboring lands which our diagnostic test showed to be spatially auto-correlated.

(4) $PastPrice_{it} = \alpha_0 + \boldsymbol{\alpha_1 Agronomic_{it}} + \boldsymbol{\alpha_2 PastCentrality_{it}} + \boldsymbol{\alpha_3 Protected_{it}} + \boldsymbol{\alpha_4 Neighbor_{it}} + W_t + \varepsilon_{it}$

(5) $CropPrice_{it} = \beta_0 + \boldsymbol{\beta_1 Agronomic_{it}} + \boldsymbol{\beta_2 CropCentrality_{it}} + \boldsymbol{\beta_3 Protected_{it}} + \boldsymbol{\beta_4 Neighbor_{it}} + W_t + \varepsilon_{it}$

We used the regression coefficients from (4) and (5) respectively in order to predict the pasture price (6) and the crop price (7) at each of the roughly 16 million ~250m pixels, *k*, in the state for each year from 2002 to 2013.

(6) $\widehat{PastPrice}_{kt} = \widehat{\alpha_0} + \boldsymbol{\widehat{\alpha_1} Agronomic_{kt}} + \boldsymbol{\widehat{\alpha_2} PastCentrality_{kt}} + \boldsymbol{\widehat{\alpha_3} Protected_{kt}} + \boldsymbol{\widehat{\alpha_4} Neighbor_{kt}} + \widehat{W}_t + \varepsilon$

(7) $\widehat{CropPrice}_{kt} = \widehat{\beta_0} + \boldsymbol{\widehat{\beta_1} Agronomic_{kt}} + \boldsymbol{\widehat{\beta_2} CropCentrality_{kt}} + \boldsymbol{\widehat{\beta_3} Protected_{kt}} + \boldsymbol{\widehat{\beta_4} Neighbor_{kt}} + \widehat{W}_t + \varepsilon$

The predictions from (6) and (7) were used as independent variables in two second stage regressions. The first (8) modeled the probability that each pixel in the state underwent pasture to crop conversion (P2C) as a logistic function of the predicted pasture and cropland prices and conversion costs as proxied with an estimate of a key element of the variation in the cost of conversion, the cost of transporting lime to every pixel. The second (9) modeled the probability that each pixel of pasture was converted to cropland using the same independent variables as (8). Due to computational limitations stemming from the large size of the 250m dataset, we performed (8) and (9) on a randomly selected dataset consisting of 500,000 pixels of the roughly 16 million pixels in the state of Mato Grosso.

(8) $prob(pixel \rightarrow P2C) = \gamma_0 + \gamma_1 \widehat{PastPrice}_{kt} + \gamma_2 \widehat{CropPrice}_{kt} + \gamma_3 \widehat{PastPrice}_{kt}^{\ 2} + \gamma_4 \widehat{CropPrice}_{kt}^{\ 2} + W_t + \varepsilon$

(9) $prob(P \rightarrow C) = \gamma_0 + \gamma_1 \widehat{PastPrice}_{kt} + \gamma_2 \widehat{CropPrice}_{kt} + \gamma_3 \widehat{PastPrice}_{kt}^{\ 2} + \gamma_4 \widehat{CropPrice}_{kt}^{\ 2} + W_t + \varepsilon$

We used the coefficients obtained from (8) and (9) to predict the likelihood of *pixel→P2C* and P2C across all of Mato Grosso. We also used the predictions from (9) to map predicted P2C on pasture (Figure 2.1) and to validate the model by comparing the probability of P2C on observed P2C vs. observed pasture vs. observed cropland.

Independent variables were obtained at a range of spatial resolutions. In cases where the spatial resolution was finer than the resolution of the entities in our analysis, we calculate entity mean values; in cases where it was coarser, we assign the local variable value to the pixel. A detailed description of all independent variables can be found in Appendix 3. Cross-sectional independent variables include daily minimum temperature ("Min Temp") averaged over the period 1981-2010; daily maximum temperature ("Max Temp") averaged over the period 1981-2010; annual precipitation ("Precipitation") averaged over the period 1981-2010; annual soil moisture ("Soil Moist") averaged over the period 1981-2010; elevation above sea level ("Elevation"); slope ("Slope"); and presence of good soils ("Good Soils"). *Good soils* is an indicator for soil suitability for both farming and ranching, and includes all soils in the Brazilian soil classification system present in Mato Grosso besides inundated soils or thin, rocky hillside soils (EMBRAPA, 2006). We also used estimated pixel-explicit cost of transporting soy from farm locations to traders or crushers averaged over the period 2000 to 2010 ("Soy Transp Cost"); estimated pixel-explicit cost of transporting cattle from ranch locations to slaughterhouses averaged over the period 2000 to 2010 ("Beef Transp Cost"); and pasture to crop conversion pixel-explicit cost averaged over the period 2000 to 2010 ("Conv Cost"). Soy Transp Cost, Beef Transp Cost, and Conv Cost were estimated using a spatially explicit transportation model developed for Cohn et al. (2014), which computes the least cost path to transport agricultural products to market and agricultural inputs to farms.

Our analysis also incorporates independent variables that vary over each year of the analysis. These include a proxy for municipality-level Beef Transport Costs ("Beeflogp"), the interaction of Beeflogp and Beef Transp Cost ("Beefint"), a proxy for municipality-level Soy Transport Costs ("Soylogp"), the interaction of Soylogp and Soy Transp Cost ("Soyint"), a proxy for municipality-level P2C Conversion Transport Costs ("Convlogp"), the interaction of Convlogp and P2C Conversion Transport Costs ("Convint"), designation as protected areas ("Prot. Areas"), designation as Indigenous Reserve ("Indig. Lands"). The method for estimating Beeflogp, Soylogp, and Convlogp are described in Pellegrina (Pellegrina, 2014).

The likelihood of any form of land use change or agricultural intensification, including P2C, depends on the characteristics of neighboring regions. A small patch of land suitable for agriculture surrounded by poor land is less likely to be developed or intensified than a patch of suitable land surrounded by suitable land (Brady & Irwin, 2011). This effect may stem not only from economies of scale within the farming sector, but also from the likelihood that such a place will also enjoy superior transportation networks, storage facilities, and the traders or suppliers that create the linkages between a commodity's production, processing, and consumption (Garrett et al., 2013). The spatial organization of an economy – and the distribution of certain production systems – influences and is influenced by elements such as the provision of goods and services, isolation from markets, and existing supply chain infrastructure. Recent studies have demonstrated spatial dependence in land use choices (Brady & Irwin, 2011) and the emergence of agglomeration economies in Mato Grosso due to a positive feedback effect between agricultural firms and producers (Garrett et al., 2013). Soybean production and beef production are governed by different spatial processes due to their specific production, distribution and marketing requirements. The extent to which this difference influences P2C will depend on farm size and economies of scale because these factors may both alter spatial dependence (Paul et al., 2004; Eastwood et al., 2010).

We modeled agricultural decisions to depend not only on the characteristics of a given parcel of land, but also the characteristics of neighboring lands, and on the interaction between each farm's characteristics and location. Using a random subset of the dataset sufficiently small for matrix multiplication in Stata MP 13, we tested for spatial dependence in all dependent variables and independent variables investigated using Moran's I, a common spatial dependence metric. The variables Past, Crop, Max Temp, Min Temp, and Precipitation were all found to exhibit spatial dependence and were then analyzed using variograms (see Appendix 2 – Figure A 2.8). These variograms depict the semi-variance of neighboring values of each observation in the dataset and reveal the appropriate range over which to control for spatial dependence. We also introduced finer scale spatial dependence controls for more localized agriculturally salient processes (i.e. the movement of machinery from field to field). We included these control variables (seven in total) in regresssions (4) and (5), using a method shown by Robertson et al. (2009) to be the most effective means of controlling for coefficient bias from spatial autocorrelation of several approaches investigated through simulation. A summary of all variables and their corresponding sources can be found in the Appendix 2 – Table A 2.1 to Table A 2.6.

2.2.3. **Qualitative research: Expert interviews**

A great deal of heterogeneity in the P2C process is unobservable in statistical analyses due to data limitations. First, fine scale biophysical variation not represented in datasets and/or arising from farm management itself can influence P2C. For example, some soils hold insufficient moisture, others degrade readily, and minor differences in climate can alter susceptibility to pests and plant diseases (Couto et al., 1997; Werth & Avissar, 2002; Farias et al., 2007; Aragão et al., 2008; Vera-Diaz et al., 2008).

Second is producers' ability to limit their exposure to commodity price risks by ranching and farming simultaneously, as shocks to crop and livestock prices can be remarkably decoupled. Production diversification through P2C can buffer variations in agricultural and livestock input prices. Mixed systems involving cattle ranching and mechanized agriculture can offer increased flexibility with regards to selling agricultural products than mechanized agricultural systems alone. The possibility to reverse the conversion process further increases the utility of the mixed system (Miao et al., 2014). However, socioeconomic factors (e.g. producers' age, education, know-how, access to capital, and investment capacity) as well as their perceptions of risk, risk attitudes, and available risk management strategies, may limit adoption.

Third, local economic and political institutions may also influence P2C. Two examples of regulatory risks are the recent changes made to the Brazilian Forest Code (including modifications in the process of environmental licensing of rural properties) and the lack of a standardized procedure for evaluating credit requests at public banks (Soares-Filho et al., 2014). Both changes may create uncertainty among producers, particularly with regards to longer-term investments in the land. In addition, higher land productivity is associated with better functioning land markets in Brazil (Assunção & Chiavari, 2014). Many local rental markets are beset by overly rigid contractual clauses, legal system failures, and insecurity of property rights (Assunção & Chiavari, 2014).

The relative importance of these factors – and the extent to which each of them may affect the advantages and disadvantages of engaging in a new activity – depend on farmers' motivations, goals and business strategies, characteristics of the farm and the farmers themselves, as well as the information acquisition and learning processes (Greiner et al., 2009; Cardenas & Carpenter, 2013). Moreover, difficult-to-observe factors such as the often underestimated utility of owning land (Deininger & Feder, 2001) and cattle (Bowman, 2012) may also explain low P2C adoption rates and the persistence of extensive cattle ranching. Both land and cattle are ways of accumulating wealth, may be used as savings and collateral, and may confer social status.

We undertook qualitative research to investigate these possible influences on P2C. The first approach was qualitative interviews with 16 land experts and other key informants such as union heads and input sellers from MT. Experts with knowledge of agriculture in frontier regions were selected from key informant lists maintained by an agricultural consulting firm. Questions for the experts covered, among others, the status of the P2C conversion process, technical parameters of farms where P2C takes place, factors influencing rancher and farmer decisions to engage in P2C, the role of land rentals in P2C, rental contract enforcement, and transaction costs. For comparison, we undertook additional interviews to collect information on P2C in the neighboring states where P2C is also common – Mato Grosso do Sul, Tocantins, and Pará. The full questionnaire administered is found in the Apprendix.

Next, we analyzed the raw data and coded all responses that addressed drivers and constraints to P2C. We classified each statement into five categories - economic, institutional, demographic, cultural, biophysical, and others. Within each category we counted recurrence, noted agreement/disagreement, and selected emblematic quotations.

2.2.4. Qualitative research: Focus groups

The second qualitative research approach was six focus groups (FGs) to examine rancher and farmer socioeconomic characteristics, personal knowledge, experience, risk perceptions, and perceptions with regards to P2C. The objective was to investigate how heterogeneity of rural producers and their farms may help to explain the complexity and dynamism of the P2C process at local level.

The FGs were conducted in the municipalities of *Juara*, *Porto dos Gaúchos* and *Vila Rica*. Brazilian municipalities are the equivalent of counties, and the FGs were held in each municipality's county seat. We selected these locations prior to performing the satellite data analysis. The locations came from a list of roughly 15 municipalities in the state identified by local agricultural experts as being places of importance for recent, present, or future P2C conversion. All three municipalities have ample pasturelands that experts identified as currently or soon to be important for P2C. *Juara* and *Porto dos Gaúchos* were selected in order to investigate conditions on both sides of a known divide between ranching and farming. Although *Porto dos Gaúchos* and *Juara* border each other, *Juara* has a reputation as a ranching-dominated municipality, whereas *Porto dos Gaúchos* already has a great deal of crop farming.

FGs participants were sampled from the rosters of local producers' unions and input suppliers, excluding producers with land holdings below 500 ha. We excluded small-scale producers for two reasons. First, our FGs were designed to reflect the profile of ranchers and farmers controlling much of the land in Mato Grosso. Rural properties smaller than 500 hectares correspond to only 15% of Mato Grosso's total registered area (INCRA, 2012). Second, preliminary interviews revealed that P2C is mostly associated with large properties and agricultural holdings. Recruitment was challenging, and strictly randomized sampling could not always be achieved. Still, our FGs present a fairly representative sample of small- and medium-scale farm holdings in MT, replicating the balance of ranchers and farmers observed in the focal municipalities.

FGs are well suited in exploratory settings because they allow participants freedom to communicate their interests and expertise (Morgan, 1997; Bloor, 2001). All FGs groups followed the same script (see Appendix 4) and were moderated by experienced agricultural consultants trained and supervised by the authors of this paper. The contents of all FGs were transcribed and systematically analyzed by the authors of this paper according to Bryman's method for qualitative data analysis, which is based on text coding, identification of major themes and key ideas, interpretation, and establishment of links to theory and to other findings (Bryman, 2012). FGs participants were also asked to answer a quantitative questionnaire for the socio-economic characterization of the population sampled in the FGs and their farm holdings.

As with the expert interview data, we noted and classified into categories all focus group data addressing drivers and constraints to P2C.

2.3. Results & discussion

The following sections present the results for each of the four research methods employed: expert interviews, FGs, remote sensing analysis, and statistical analysis.

2.3.1. Remote sensing analysis

We found roughly 1.6 million hectares of P2C expansion in MT from 2000 and 2013. This constituted 49% of all pasture expansion during the period. Because of our conservative definition of total pasture area (as explained in the Material and Methods section), we find a much lower area of P2C than found by Macedo et al. (2012) from 2001 to 2010. We mapped approximately 7 million hectares of cropland and 22 million hectares of pasture in 2012/13.

Figure 2.1 shows land use in Mato Grosso in year 2012/2013. Just 1.2 million hectares of all 1.6 million hectares of identified P2C remained as cropland in 2012/13, indicating that the process is sometimes temporary. As illustrated by Figure 2.1D, there are three main centers of P2C in Mato Grosso. Two of them are near existing crop production centers: i) the central circle comprises three municipalities near Sorriso (*Vera*, *Claudia*, and *Ipiranga do Norte*); and ii) the left circle contains two municipalities along the BR-364 highway (*Diamantina* and *Campo Novo do Parecis*). The third center, contained in the rightmost circle, is found along the BR-158 highway east of the Xingu Indigenous Reserve. It is not near any established centers of mechanized agriculture and comprises larger contiguous areas of P2C.

In total, we found 14,962 contiguous patches of P2C in 2012/13. 99% of the patches were less than or equal to 1,210 hectares. Though the vast majority of P2C instances were very small scale relative to the farm size of focus group participants, this measure of patch size is not necessarily related to farm size. More than half of all P2C area came from the top 1% by size of contiguous areas (see Appendix 2 – Table A 2.11).

P2C in the Northeast of Mato Grosso is located on lands that have significantly less neighboring mechanized agriculture than the rest of the state (Mechanized agricultural density, proxied with the spatial control variable “sp_crop381km” is shown in Figure 2.1D). In the NE, the mean cropland density of lands neighboring P2C was just 80% of the statewide cropland density mean. By comparison, the mean cropland density of all P2C is 140% of state average Cropland Density.

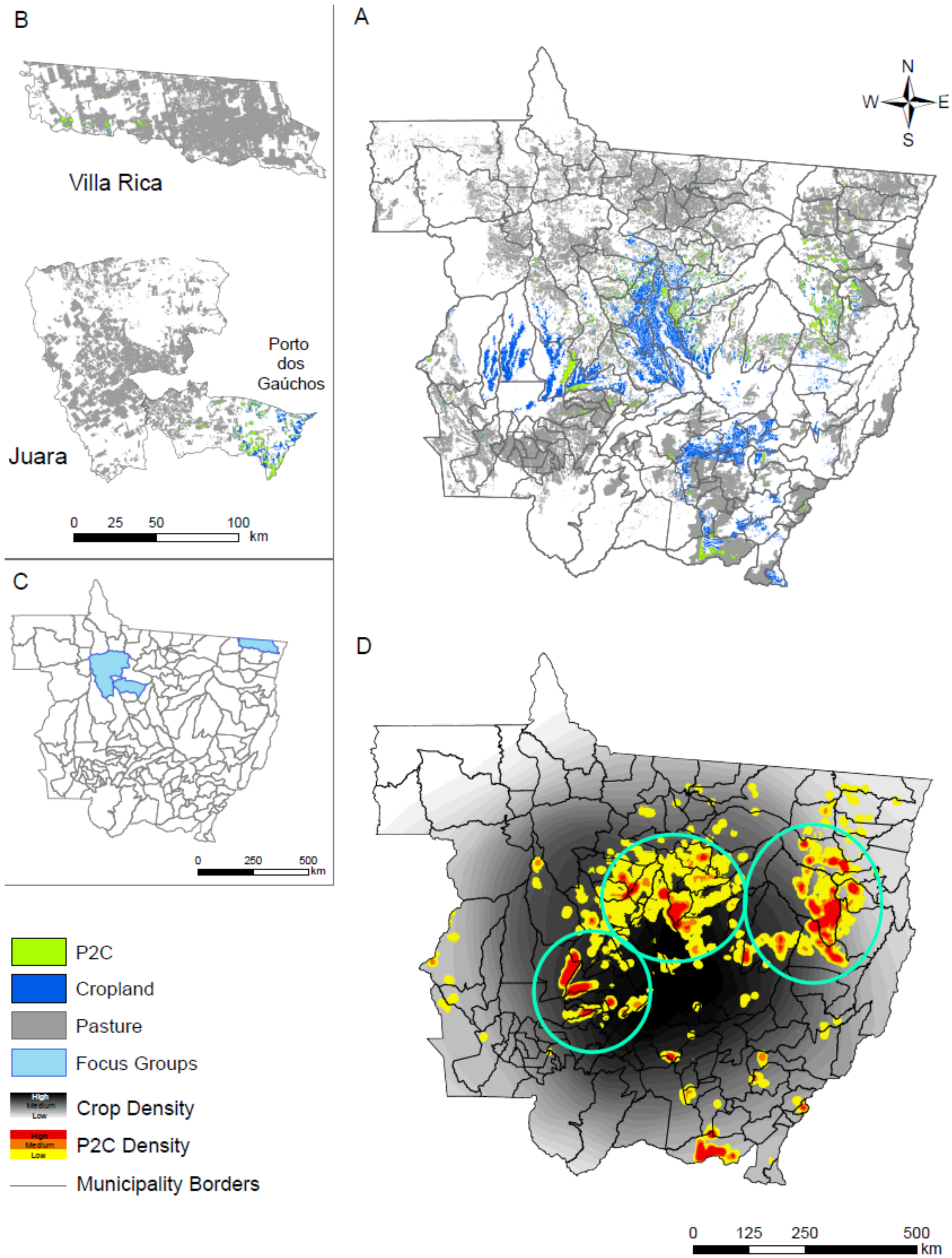

Figure 2.1. (A) Pasture area, cropland, and P2C in Mato Grosso. (B) Pasture area, cropland, and P2C in the focal municipalities Juara, Vila Rica, and Porto dos Gaúchos. (C) Thumbnail of Mato Grosso showing the exact location of the three focal municipalities in the state. (D) Density pf P2C vs. density of cropland in Mato Grosso. P2C density is a count of all pixels of P2C within a 10km radius. Crop density is a count of all pixels of cropland in a 38km radius.

P2C in 2012/13 was closer to roads and agricultural centers than pasture, but less centrally located than other cropland. Significantly more ($p<0.01$) cropland (80%) was found within 10km of federal highways in Mato Grosso than P2C (71%). P2C was found to be near areas of intensive cropland production. Two sample t-tests revealed that Harvest density, a proxy for centrality with respect to mechanized agriculture output, was significantly greater ($p<0.01$) for P2C areas (1,271 km^2) than the state as whole (483 km^2) or Pasture (297 km^2), but significantly less ($p<0.01$) than Cropland (2,989 km^2).

2.3.2. **Statistical analysis of the likelihood of P2C conversion**

We estimated hedonic models to quantify the relationship between observed cropland prices with land characteristics and observed pasture prices with land characteristics (a synopsis of independent variables classed as representing agronomic conditions, centrality, protected areas, and neighborhood characteristics can be found in Table A 2.2, Table A 2.4 and Table A 2.6 in Appendix 2). Roughly 20% of the variation in cropland prices and 16% of the variation in pasture prices were associated with the vector of variables employed in the regression intended to represent agronomic land quality (Table 2.3 shows the share of the variation in land prices associated with each class of variable). Neighborhood characteristics explained 53% of the variation in cropland price but just 3% of the variation in pasture price. By contrast, while 64% of the variation in pasture price was associated with time dummies, these explained just 15% of the variation in cropland price. This indicates that while cropland expansion is highly sensitive to location, pasture expansion depends more on location-independent fluctuations. Further, non-agronomic characteristics of cropland location play a much larger role than agronomic characteristics, perhaps suggesting the importance of infrastructure and supply chain proximity for crop production. The low importance of agronomic characteristics relative to neighborhood characteristics may simply reflect an abundance of land agronomically suitable for cropping. Both the pasture price and the cropland price model exhibited high skill in predicting land price observations withheld from the analysis as a test dataset.[5] Full regressions results and robustness checks are found in Appendix 2.

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[5] To ensure that these predictions were valid, we split the dataset into a test dataset of 500,000 randomly selected observations and a training dataset of the remaining roughly 16 million pixels. We then re-estimated the regressions on the training data set alone. We predicted the land prices in the test dataset and then compared the adjusted r^2 from the training prediction with the adjusted r square from the full sample. They were the same to four decimal places.

Table 2.3. Effect Size of determinants of land price variation

	Portion of variation explained ($\eta 2$)	
	Cropland	Pasture
Agronomic	20.9%	15.7%
Centrality	9.3%	12.1%
Neighborhood	53.5%	3.4%
Protected areas	0.7%	4.3%
Time	15.6%	64.6%

Next, we generated predicted pastureland prices and cropland prices for each pixel in Mato Grosso. We used these as independent variables second stage regressions in which we characterized the likelihood of pasture to crop conversion as a function of crop price, pasture price, and a set of proxy variables for the cost of converting pasture to cropland. We found that P2C likelihood was positively associated with higher land prices. However, it was negatively associated with the square of the price of both pastureland and cropland. Thus, the likelihood of P2C is greatest on lands with middle range prices at the fringes of agricultural regions.

Seemingly contrary to theory, higher conversion costs were associated with a higher likelihood of P2C. This likely indicates that the true conversion costs contain many non-observed variables beyond the cost of transporting lime to future farmland and helps to motivate our qualitative research on statistically unobserved conversion costs. Full regression tables and descriptive statistics can be found in Appendix 2.

We then predicted probabilities of P2C using coefficients from a training dataset (n=500,000 pixels) on all remaining land in MT (n=15,507,297). These predictions can be interpreted as tests of the similarity of the characteristics of P2C vs. Crop vs. Pasture vs. the rest of Mato Grosso (full results are shown in Table 2.4). Each land category was found to be significantly different from each other category. Pasture and the Rest of the State were similar to each other in having lower predicted P2C likelihood. Cropland and P2C were similar in having higher predicted P2C likelihood. Paired t-tests revealed that all four means were significantly different from each other.

Table 2.4. Predicted Likelihood of P2C by land use type.

Land Use	Area in 2012/13 (ha)	Likelihood of P2C	Std.Dev.
Pasture	21 280 392	3.2%	2.0%
Cropland	4 298 792	5.2%	1.4%
P2C	1 264 032	5.5%	1.9%
Rest of the state	63 357 095	2.7%	2.0%

The predictions on pasture also help to illustrate possible future P2C (Figure 2.2). Just 10% of remaining pasture in MT had a greater than 7% predicted likelihood of conversion to cropland.

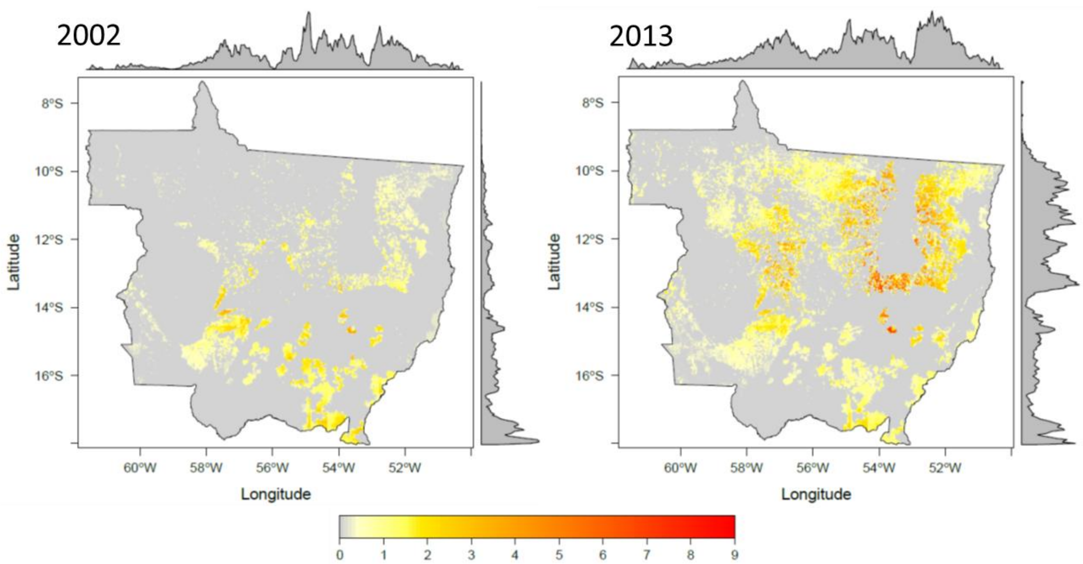

Figure 2.2. Predicted probability of the conversion of pasture to cropland in 2002 (left) and 2013 (right) in Mato Grosso. The legend depicts the likelihood pf pasture to crop conversion in percentage term. Grey shaded line plots at the top and right of the figure represent longitudinal and latitudinal distribution, respectively. The maps illustrate the increasing likelihood pf P2C in the study period, particularly in the Northeastern region of the state.

2.3.3. **Expert interviews**

We performed semi-structured interviews on P2C trends with 16 land experts from MT and three neighboring states (Mato Grosso do Sul, Tocantins, and Pará). Table A 2.15summarizes experts' perceptions of drivers and constraints of P2C. All subjects stressed two insights: (i) P2C is driven by the need to restore degraded pastures and (ii) P2C can be constrained by unfavorable farming conditions / limited land suitability. Three points of divergence were whether conversion is more likely helps retain water in areas of sandy soils; the level of risk from poor contract enforcement under P2C rentals; and whether limited qualified labor constrains pasture conversion and/or crop farming.

Experts were asked to assess the importance of farm characteristics, agronomic land quality, centrality, land prices, and institutional factors in influencing P2C likelihood. The top three categories emphasized as important were, respectively, agronomic land quality, relative prices of pasture vs. cropland, and farmer demographics (Full results can be found in Table A 2.16).

Experts expected that crop farmers were responsible for more P2C than ranchers because of competitive advantage through access to equipment, infrastructure, technical expertise, and specialized labor. Experts also asserted that the primary P2C agents have been large landholders who can use economies-of-scale to offset logistics-related costs beyond those compensated by low cropland prices. The Northeast part of MT was specifically mentioned as a favorable region for cropland expansion, where securing land tenure may be a less politically fraught process than in other parts of the state. Experts believed that this has already attracted large-scale operations by foreign investors and might contribute to turning the Northeast into a P2C hotspot.

The interviews also revealed contrasts in frequency, drivers, and outcomes of the three distinct mechanisms of P2C—rentals, sales, and self-conversion. On average, they estimated self-conversion to comprise 12% of the total P2C in the state, with sales responsible for 33% and rentals the mechanism for 55%.

P2C through rentals vs. P2C through sales may have different drivers and characteristics due to their temporary vs. permanent character. Farmers' willingness to invest in the short-term is comparatively lower in case of rental contracts. Thus, renters may care more about soil conditions than buyers, who may look for undervalued properties with degraded soils to restore. Rentals were also seen as a way to bypass bureaucracy associated with land sales. Processing land sales can take years. Credit for land is typically unavailable, but transactions that are conditional on credit access may also be delayed by environmental licensing and due diligence.

2.3.4. **Focus groups**

Two focus groups (FGs) were conducted in each of three municipalities deemed by experts to be P2C hotspots—Juara, Vila Rica, and Porto dos Gaúchos (their location is depicted in Figure 2.1B and Figure 2.1C). Of the 53 participants, about half (26) identified themselves as only ranchers, 6 considered themselves only farmers, 14 considered themselves both ranchers and farmers, 5 had other occupations, and 2 declined to respond. Participants saw pasture to crop conversion as a recent development in their municipalities. All participants had already heard about P2C, but less than half (n=18) had engaged in it. Out of those, 6 rented land from someone else, 16 rented their own land to someone else, 5 did both, and 1 declined to respond (additional results obtained through questionnaires administered to FG participants can be found in Table A 2.18).

Ranchers said that they decided to rent their land when (a) their soil was degraded, especially if they lack capital or know-how to restore its fertility or (b) when opportunity costs of renting for cropping exceed the profits from cattle but they still want to keep the land. Many of those who elected to remain in cattle ranching were motivated by a sense of cultural and/or professional identity as a rancher and an emotional attachment to ranching. In addition, participants in all six FGs saw ranching as less risky than farming. Ranchers who have elected to leave ranching were motivated labor shortages stemming from the rural exodus among younger generations and/or because they faced bankruptcy.

Producers from all FGs agreed that the vast majority of P2C has involved land transactions (either renting or buying). They claimed that the low share of self-conversion relative to the other two P2C pathways is mainly due to ranchers' limited financial capacity to establish crop farming on their properties.

Renters and buyers had different motivations and identities. Renters wanted to take advantage of temporary market conditions or lacked capital. Buyers sought longer-term returns and were willing to engage in more permanent investments. Participants also talked about the growing influence of investment groups as buyers with the luxury to buy lands at the best moment and with the ability to pay rent up front.

The risk of land rental contract breaches was discussed four of the six FGs and debated in two. The two most common problems faced by lessors were reported to be (a) the delay of payments due to low yields and (b) farmers not leaving the land at the agreed-upon-time. Producers from all six FGs agreed that that they could not rely on formal sanctioning against lack of contract enforcement. They used peer networks for careful selection of low risk business partners.

2.3.5. **Comparison of focus groups with expert interviews**

Results from the FGs and expert interviews revealed more similarities than differences regarding stated drivers and constraints of P2C, even though the former primarily addressed personal experiences while we asked the latter to characterize P2C at a more aggregate level. Common themes included: (a) land transactions as the primary mechanism for P2C; (b) the importance of non-production utility of holding land as constraint on P2C; (c) the socio-cultural differences between farmers and ranchers; (d) the differential drivers of each of the three P2C conversion pathways; (e) the varying risk profile of producers; (f) informal institutions supporting agribusiness activities; and (g) the differential risks faced according to producer characteristics.

One notable set of contrasts stems from a difference in the farm size of focus in FGs vs. the Expert Interviews. For the FGs, we targeted producers larger than 500 hectares and achieved a fairly large average farm size of respondents (3,088 ha). Yet, in addition to discussing farms of roughly the size highlighted in the FGs, our experts also addressed larger farms (sometimes 10 or even 100 times larger). This alternate focus explains why more than half of the experts discussed business risks of P2C in ways that differed from the FGs. Investigating the operations of very large farms is crucial for understanding land use in MT, as just 20% of all producers control over 80% of the registered agricultural land in the state (INCRA, 2012) and highly differential farm economics are found in the region according to farm size (Assunção et al., 2012).

2.3.6. **Municipality tendencies in focus groups vs. spatial analysis**

As can be seen in Figure 2.1D, two of the three FGs locations, Juara and Vila Rica, were far outside of the P2C hotspots identified. That prompted us to develop comparisons between the mapped data, statistical models, and claims made in the FGs about the focal municipalities. Because FGs participants mirrored the producers in the three municipalities and because much of the FG discussion was dedicated to each municipality as a whole, we compared focus group and spatial analysis at the level of each focus group municipality.

The first FG claim we investigated was that the focal municipalities were P2C hotspots. We found that P2C rates in *Juara* (0.1%) and *Vila Rica* (0.6%) were below the MT average of 1.4%. *Porto dos Gaúchos* had an above average rate of 5.1% (see Table 2.5). All three focal municipalities contained far more pasture than cropland. The discrepancy between the FG claims and the spatial results might be an indication that the P2C was recent (occurring after

2012/13 and thus not captured in our maps). Or, perhaps, the focus groups have revealed near-term expectations in addition to recent outcomes. The forwarding-looking potential for FGs can provide a helpful complement to the retrospective nature of the spatial analyses. FGs draw attention to the dynamic nature of the P2C process, particularly to changing producers' expectations and their influence on P2C.

Table 2.5. Areas under different land use classes for focal municipalities, Northeastern MT and the entire state of Mato Grosso (in hectares and as percentages).

Focal municipality	Area (ha)				
	Total	Rest of MT	Crop	Past	P2C
Juara	2 257 320	1 489 700	85	767 451	2 195
	100%	66.0%	0.0%	34.0%	0.1%
Porto dos Gaúchos	697 133	419 017	37 820	202 476	35 895
	100%	60.1%	5.4%	29.0%	5.1%
Vila Rica	747 833	295 398	310	451 814	4 453
	100%	39.5%	0.0%	60.4%	0.6%
Northeast	5 847 216	3 848 619	98 511	1 599 508	300 578
	100%	65.8%	1.7%	27.4%	5.1%
Mato Grosso	90 335 700	60 967 062	5 563 803	22 537 935	1 266 900
	100%	67.5%	6.2%	24.9%	1.4%

The second FG claim was that each focal municipality contains a great deal of pasture of high conversion propensity. Our statistical models suggest that *Juara* may never become an established cropping area (see Table 2.6). Across all cropland expansion models investigated, the mean predicted probabilities of *Juara*'s pastures were as much as one order of magnitude smaller than the state average. *Vila Rica* was also of below-average predicted probability of conversion. By contrast, the pastures of *Porto dos Gaúchos* were of above-average conversion potential, in line with the high incidence of P2C observed there. Non-agricultural areas were of higher conversion propensity than pastures in the majority of cases investigated. Perhaps FG participants are misguided about the potential for P2C in their municipalities, but it could also be that they have an accurate view of future conversion potential. Moreover, it is possible that future P2C could occur on land that is different from past P2C, which is in line with our argument that land institutions and other variables, unobservable or omitted from our statistical models, may strongly influence P2C.

Table 2.6. Mean predicted probabilities of the likelihood of conversion of pasture and non-pasture areas into "P2C" in the three focal municipalities (Juara, Porto dos Gaúchos and Vila Rica), Northeast of MT and in MT as a whole. Numbers in italics are standard deviations.

	Pasture	**Non-pasture**
Juara	**4.40%**	**6.80%**
	3.60%	*5.40%*
Porto dos Gauchos	**7.10%**	**11.90%**
	5.70%	*7.00%*
Vila Rica	**3.70%**	**5.00%**
	2.90%	*3.70%*
Northeast	**6.20%**	**7.20%**
	6.50%	*8.20%*
Mato Grosso	**6.20%**	**7.20%**
	6.50%	*8.20%*

The third FG claim was that proximity to roads increases the likelihood of P2C within the municipality. We tested this claim using two-sample t-tests performed to compare, in each municipality, mean Soy Transp. Costs from P2C areas vs. other areas. In *Porto dos Gaúchos* and *Juara*, P2C was significantly more likely to occur on lands with lower logistics costs than the rest of the municipality ($p<0.01$), whereas in Vila Rica P2C occurred on lands with higher transport costs ($p<0.01$). This result might be explained by the possibility that P2C conducted by large, less income constrained investors might explain the case of Vila Rica, as they may be able to compensate for higher transport costs with economies of scale. It is also possible that producers' claims reflect their preferences but do not necessarily reflect land use at the aggregate level.

The final FG claim we investigate is that degraded soils are more likely to be converted than other soils. We were not able to access maps of soil degradation, but some soil types are known to be at lower risk of degradation than others. We thus investigate the frequency of P2C on "Good Soil" vs. other soil in each municipality. An additional set of two-sample t-tests revealed that the percentage of P2C that occurred on "Good Soil" was significantly higher ($p<0.01$) than the mean percentage of good soils in *Juara* and *Vila Rica*. In *Porto do Gaúchos*, the entire municipality is classified as "Good Soil." This homogeneity highlights the limits for inferences from national soils maps commonly employed in spatial analysis. Satellite-based LUC analysis is often conducted using coarse soil suitability maps that only distinguish arable and non-arable land, assuming that arability alone is a sufficient description of soil suitable for expansion of crop production systems. However, FGs revealed that producers are much more selective than that, and their choices to convert pastures into cropland are influenced by the level of degradation and the presence of sandy soils along with the institutional aspects of conversion. The fine scale variation in the contents of sand vs. clay in the soils is not capture by coarse national maps. In addition, the extent of soil degradation is not captured in conventional soil maps.

2.3.7. **Northeastern Mato Grosso hotspot: expert interviews vs. spatial analysis**

We decided to put additional focus on the Northeast of Mato Grosso, a region our experts described as a P2C hotspot that does not share all characteristics of cropping centers in Mato Grosso. Indeed, five municipalities (see Figure 2.3) in the Northeastern Mato Grosso were found to contain just 6% of the state's area, 6% of the state's cropland, but 25% of the state's P2C.

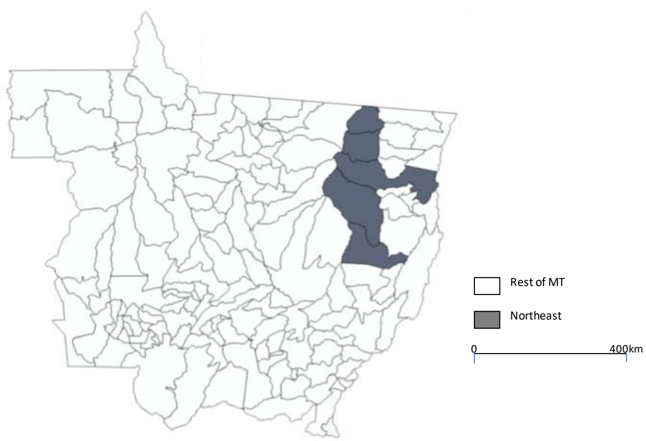

Figure 2.3. Map of five selected municipalities in Northeastern Mato Grosso.

Experts' claims that P2C in the NE is more likely to be conducted by large entrepreneurs/investment groups attracted by large contiguous plots of land is corroborated by an analysis showing that the average size of contiguous pasture areas in the region is roughly three times the statewide average (see Appendix 2 – Table A 2.12). Northeastern land prices have distinctly different portions of variability explained by independent variable groups than do land prices in the state as a whole. The Northeast is particularly remote with respect to cropping infrastructure—its mean logistics costs were significantly higher than other major cropping regions.

2.4. Conclusions

Our results demonstrate patterns and processes of P2C in Mato Grosso by drawing on a mixture of quantitative and qualitative methods that operate at a variety of scales and units of analysis. By comparing the results obtained through each of those methods, we were able to assess their concordance. Different methods highlighted different aspects of P2C and were, therefore, complementary.

P2C is a form of agricultural intensification that also entails cropland expansion. Because changes in cropland can be readily mapped using new methods for the classification of satellite data, P2C provides a unique opportunity to generate reliable spatial explicit data depicting agricultural intensification. Comparison of this aggregate spatial view of agricultural intensification with farm-level analysis of agricultural intensification can generate rich insights.

We used focus groups and expert interviews to shed light on farm decision-making processes underlying the statistical analysis. It is evident that not only institutional, but also biophysical dimensions of P2C were unobserved, unobservable, and/or highly spatially heterogeneous at the landscape level. Meanwhile, the statistical analysis allowed us to check and contextualize insights and claims from the expert interviews and FG discussions. Our mixed-method approach allows for a more holistic understanding of the P2C process within the broader context of agricultural intensification in MT and provides insights into the possibility of scaling up findings from municipalities and scaling down state-level spatial analysis (Small, 2011).

We showed that land attributes are associated with only a small portion of the variation in the location of P2C within Mato Grosso. Part of our explanation for the heterogeneous pattern of P2C is that it is established through three distinct pathways – self conversion, rentals, and sales. Land attributes differentially influence the rates and patterns of each P2C pathway. Farm heterogeneity, producers' motivations and decision-making processes, cultural and psychological factors, as well as semi-functional land institutions all also shape the heterogeneity of P2C.

Mato Grosso is at the heart of the world's fastest growing agricultural region (Graesser et al., 2015). P2C influences how much agricultural growth in MT stems from cropland expansion and agricultural intensification. Thus, P2C has implications for the science and policy of the environmental impacts of meat production; bioenergy, biofuels and biomaterials; the environmental and economic consequences of climate impacts on agriculture; and the potential for global food security (Lambin & Meyfroidt, 2011; Lobell et al., 2013; Searchinger et al., 2015). The conversion of pasture to cropland follows patterns and processes that differ from the remainder of cropland expansion and agricultural intensification and P2C itself is a heterogeneous process.

Several additional research approaches could be combined with the methods described to provide fuller understanding of P2C and other forms of agricultural development. Surveying producers found at randomly sampled points could ensure spatially representative producer data, allow the validation of land use analysis results, and enable investigations of the influence of producers' characteristics on their land use. P2C is a new and evolving process that should have its changing nature and drivers be monitored and researched. Finally, insights into P2C patterns and processes can be used to support modeling of P2C and its impacts. Approaches able to capture the interplay between natural resources and human decisions and able to represent both the aggregate characteristics of LUC and the heterogeneous, individual decision making processes of landholders are particularly apt for researching P2C (Liu et al., 2007; Bond-Lamberty et al., 2014). Together, these advances can aid the design of policy interventions effective at controlling P2C and its economic and environmental impacts.

2.5. Acknowledgments

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2.7. Appendix 1 – Mapping

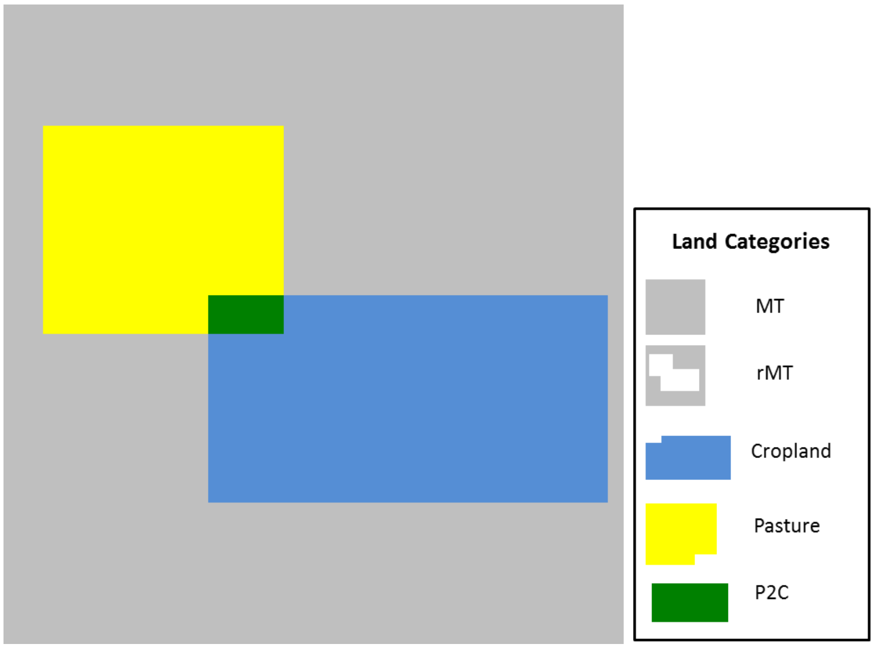

Figure A 2.1. Schematic representation of the land use categories as used in the paper.

2.8. Appendix 2 – Statistical Analysis

Table A 2.1. Description of independent variables.

IV name	Abbreviatio	Type	Resolution	Unit	Description	Source	Time
Max Temp	tmax	continuous, cross-sectional	0.5 deg	degrees C	Climate Research Unit 3.2 Annual Mean Maximum Temperature Data	New et al., 2002	1981-2010
Min Temp	tmin	continuous, cross-sectional	0.5 deg	degrees C	Climate Research Unit 3.2 Daily Mean Minimum Temperature Data	New et al., 2002	1981-2010
Precipitation	prec	continuous, cross-sectional	0.5 deg	mm	Climate Prediction Center (CPC) average annual precipitation across Mato Grosso from 1981 to 2010	Fan & Van Dool, 2004	1981-2010
Soil Moisture	soilm	continuous, cross-sectional	0.5 deg	mm	Climate Prediction Center (CPC) average annual soil moisture across Mato Grosso between 1981 and 2010	Fan & Van Dool, 2004	1981-2010
Elevation	elev	continuous, cross-sectional	90m	m	Shuttle Radar Topography Mission (SRTM) digital elevation map	Van Zyl, 2001	2001
Slope	slope	continuous, cross-sectional	90m	degrees	Shuttle Radar Topography Mission (SRTM) derived slope	Van Zyl, 2001	2001
Soy Transp Cost	soycost	continuous, cross-sectional	1km	USD/t soy	Soy farm to market logistics cost estimate	Cohn et al., 2014	2000-2010
Beef Transp Cost	beefcost	continuous, cross-sectional	1km	USD/t beef	Beef farm to market logistics cost estimate	Cohn et al., 2014	2000-2010
Good Soils	goodsoil	binary, cross-sectional	n.a.	-	includes all soils in the Brazilian soil classification system present in Mato Grosso besides inundated soils or thin, rocky hillside soils	Embrapa, 2014	1981
Indig Lands	ir	binary, time-series	-	-	designation as Indigenous Reserve in the year 2012/13	IUCN & UNEP 2014	2002-2013
Prot Areas	pa	binary, time-series	-	-	designation as protected areas in the year 2012/13	IUCN & UNEP 2014	2002-2013
NE	NE	binary, cross-sectional	-	-	Five muncipalities in Northeastern Mato Grosso, Canarana, Querencia, Sao Jose do Xingu, Santa Cruz do Xingu, Sao Felix do Araguaia	n.a.	n.a.
Conversion costs	conversion	continuous, cross-sectional	1km	USD/t lime	Estimated cost of transporting lime to each pixel from the closest of the two major sources of lime in Mato Grosso	ABRACAL, 2014	2000-2010
Predicted cropland price	croppricepr	continuous, time-series	250m	BRL/ha	Land prices observations collected by the agricultural consulting company FNP	Richards, Walker & Arima, 2014	2002-2013
Predicted pasture price	pastpricepr	continuous, time-series	250m	BRL/ha	Land prices observations collected by the agricultural consulting company FNP	Richards, Walker & Arima, 2014	2002-2013
SoyLogP	soylogp	continuous, time-series	municipality	USD/t	Proxy for municipality-level Soy Transport Costs	H. Pellegrina, 2014	2002-2013
BeefLofP	beeflogp	continuous, time-series	municipality	USD/t	Proxy for municipality-level Beef Transport Costs	H. Pellegrina, 2014	2002-2013
ConvLogP	convp	continuous, time-series	municipality	USD/t	Proxy for municipality-level Lime Transport Costs	H. Pellegrina, 2014	2002-2013

Table A 2.2. Summary statistics of the independent variables.

Variables	Mean	Std.Dev.	Min.	Max.
tmax	32.16	0.59	30	33
tmin	19.72	0.67	18	21
prec	1764.72	264.47	1072	2767
soilm	5326.81	424.63	4289	6312
elev	335.77	141.14	77	1118
slope	1.72	2.18	0	32
soycost	73.03	34.73	11	194
soylogp	389.03	122.31	191	587
beefcost	243.38	115.03	61	623
beeflogp	2.90	0.73	2	4
goodsoil	0.80	0.40	0	1
ir	0.14	0.35	0	1
pa	0.04	0.19	0	1
croppricepr	1.50	0.87	0	5
pastpricepr	1.40	0.55	0	3
conversion	438.80	46.65	362	592
convp	195.97	61.52	96	296
Observations	16007297			

Table A 2.3. Description of spatial control variables.

Spatial control variables	Neighborhood distance (km)	Description
crop5km	5	Count of all pixels of cropland within 5km radius of observation
tmin40km	40	Mean minimum temperature within 40km of observation
tmax40km	40	Mean maximum temperature within 40km of observation
prec40km	40	Mean annual precipitation within 40km radius of observation
crop381km	381	Count of all pixels of cropland within 381km radius of observation

Table A 2.4. Summary statistics of the spatial control variables.

Variables	Mean	Std.Dev.	Min.	Max.
focalag20135km	85	216	0	1373
focaltmin40km	197182	6337	180352	211610
focaltmax40km	321550	5613	304467	332801
focalprec40km	1765	255	1089	2444
focalag381km	412818	241226	64	866997
Observations	16007297			

Table A 2.5. Description of additional variables used in this paper.

Variable	Description	Source
Biomes	Shows the portion of MT in Cerrado, Amazon and Pantanal biomes	http://mapas.mma.gov.br/i3geo/datadownload
Near highways	Land within 10km of federal highways in MT	Mato Grosso State Secretary of Planning, 2013

Table A 2.6. Summary statistics of the dependent variables.

Variables	Mean	Std.Dev.	Min.	Max.
lq4p	2038.2	741.4201	479	4275
lq8p	3734.431	1921.243	830	9200
p2c	0.0031469	0.0560088	0	1
Observations	16007297			

Table A 2.7. First stage regression results.

Variable	(2) lq4p	(4) lq4p	(3) lq8p	(5) lq8p
tmin	**70.094*** *-3.491*	**-98.965*** *-18.084*	**-2352.601*** *-12.389*	**-941.322*** *-64.63*
tmax	**79.177*** *-3.957*	**394.901*** *-22.26*	**2452.385*** *-13.057*	**1269.898*** *-75.342*
prec	**0.590*** *-0.009*	**-0.027** *-0.02*	**-2.033*** *-0.025*	**1.095*** *-0.051*
soilm	**0.063*** *-0.006*	**-0.108*** *-0.007*	**0.460*** *-0.019*	**-0.282*** *-0.021*
elev	**0.456*** *-0.011*	**0.265*** *-0.012*	**2.377*** *-0.039*	**-0.316*** *-0.042*
slope	**-8.503*** *-0.489*	**-8.215*** *-0.5*	**89.563*** *-2.818*	**161.790*** *-2.879*
pa	**25.557*** *-12.911*	**73.137*** *-12.882*	**1005.707*** *-63.636*	**921.627*** *-61.69*
ir	**-541.831*** *-7.422*	**-520.065*** *-7.415*	**-765.643*** *-45.024*	**-473.216*** *-43.648*
goodsoil	**372.499*** *-2.805*	**362.715*** *-2.803*	**1508.350*** *-16.855*	**1246.850*** *-16.403*
transpcosts	**-2.509*** *-0.037*	**-2.250*** *-0.038*	**-28.949*** *-0.477*	**-25.728*** *-0.465*
logp	**-1.43e+05*** *-1510.226*	**-1.24e+05*** *-1575.692*	**-16.236*** *-6.432*	**-163.552*** *-6.781*
transpint	**-0.682*** *-0.011*	**-0.724*** *-0.011*	**-0.032*** *-0.001*	**-0.028*** *-0.001*
ag5km		**0.072*** *-0.005*		**0.809*** *-0.008*
tmin40km		**0.023*** *-0.002*		**0.031*** *-0.007*
tmax40km		**-0.049*** *-0.002*		**-0.153*** *-0.008*
prec40km		**0.852*** *-0.021*		**-3.553*** *-0.062*
ag381km		**0.000*** *0*		**0.003*** *0*
Constant	**2.44e+05*** *-2612.071*	**2.14e+05*** *-2700.737*	**-2.53e+04*** *-1362.073*	**60739.259*** *-1601.327*
R-squared	0.569	0.573	0.512	0.544
Observations	540398	540398	361019	361019
Model	500+log int. crop	500+log+neigh. int crop	500+log int. crop	500+log+neigh. int crop

*** p < 0.05, ** p < 0.01, *** p < 0.001**

Table A 2.8. Second stage regression results, part 1.

Variable	(8)	(9)
croppricepr	**1.725*** **	**1.536*** **
	-0.063	*-0.073*
pastpricepr	**3.891*** **	**4.062*** **
	-0.188	*-0.236*
chat	**-1.031*** **	**-0.791*** **
	-0.033	*-0.037*
phat	**-0.058**	**-0.12**
	-0.085	*-0.102*
conversion	**0.012*** **	**0.023*** **
	-0.001	*-0.001*
convp	**2.016*** **	**1.920*** **
	-0.035	*-0.041*
convint	**0.000*** **	**0.000*** **
	0	*0*
Constant	**-625.330*** **	**-596.872*** **
	-10.678	*-12.467*
R-squared	0.062	0.054
Observations	5991984	1024632
Model	500 Whole state+YearFE	500 Pasture+YearFE

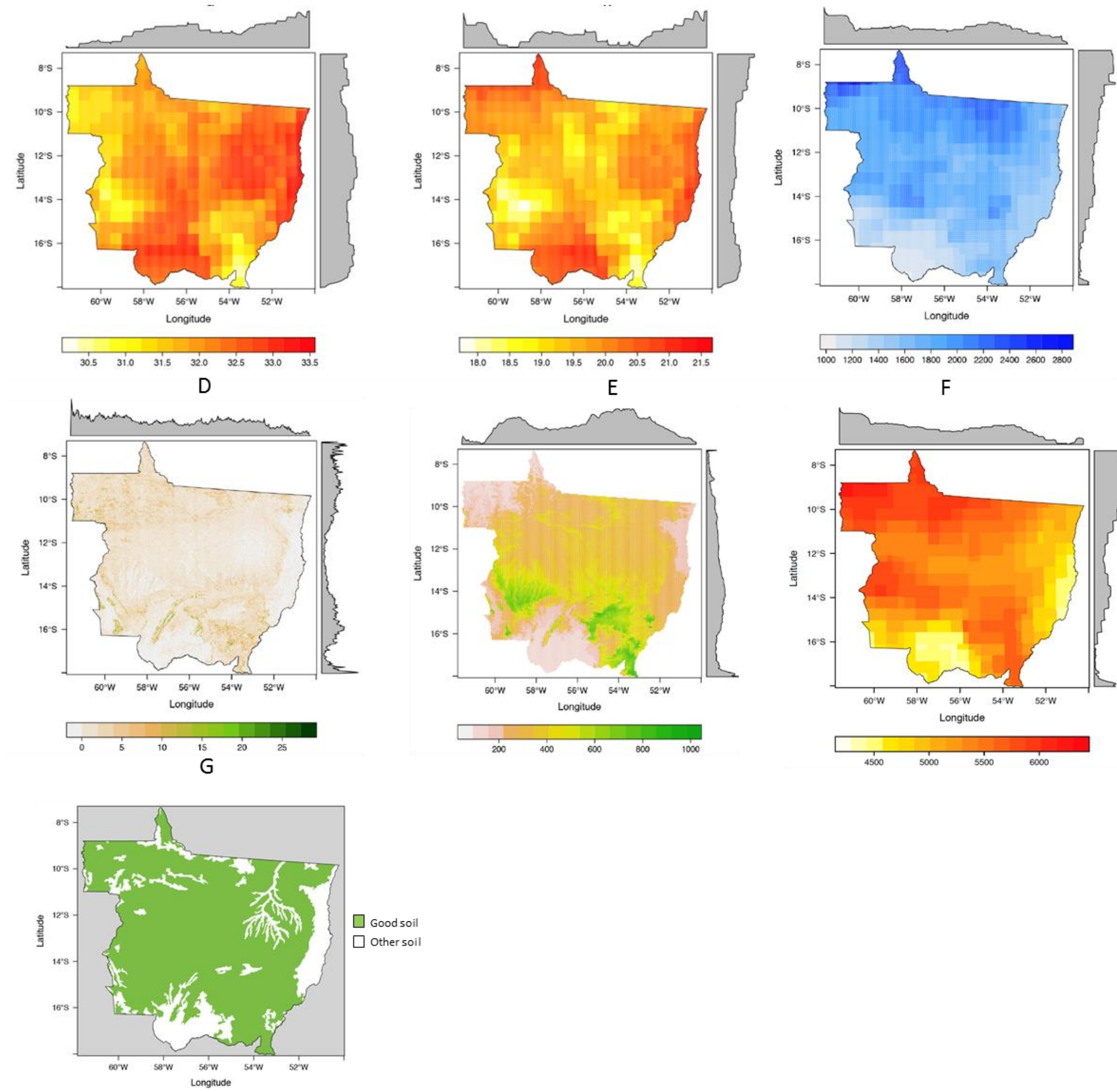

Figure A 2.2. Maps of agronomic suitability variables. A- tmax B- tmin C-prec D-slope E-elev F-soilm G-good soil.

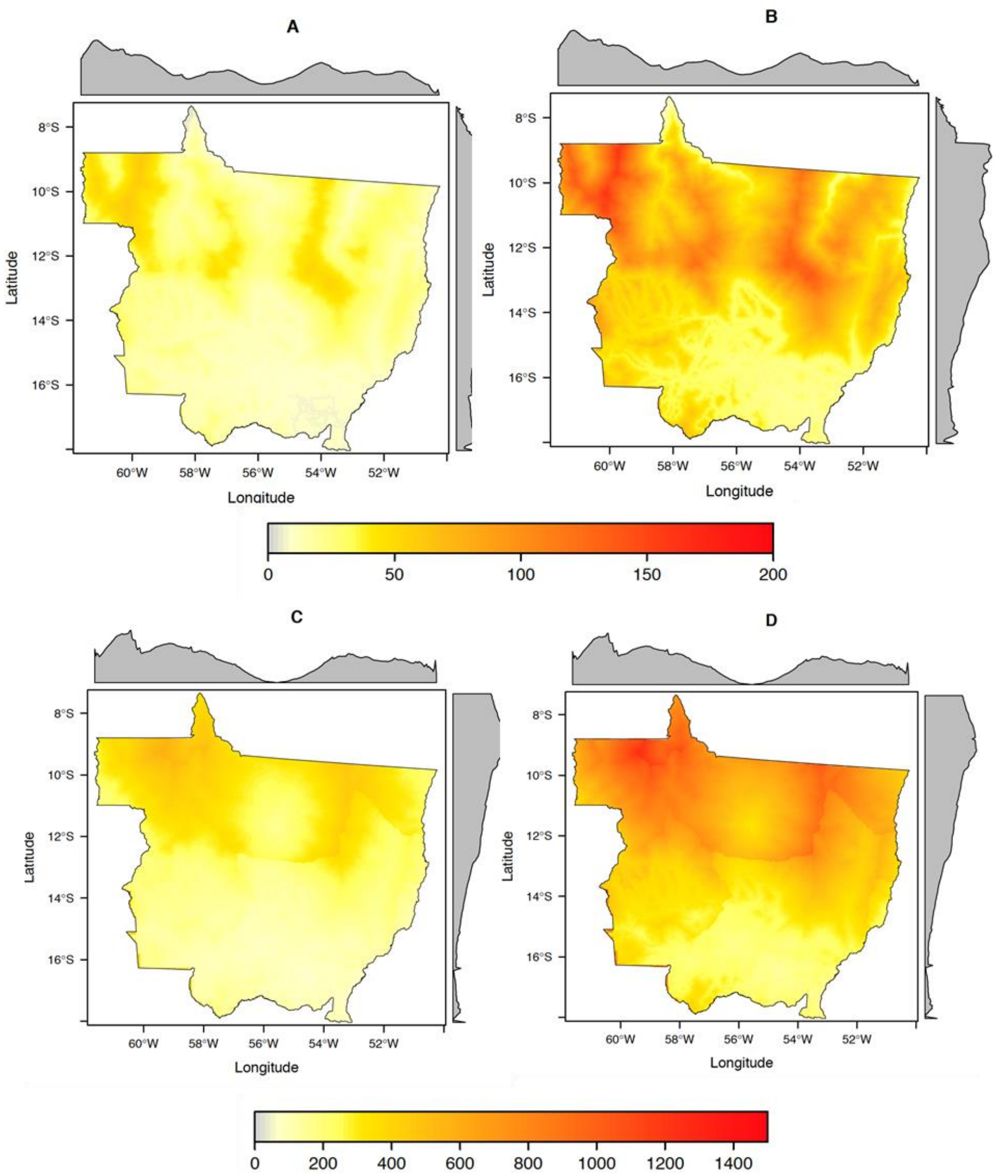

Figure A 2.3. First stage logistics variables. A- soyint2002 B- soyint2013 C-beefint2002 D- beefint2013.

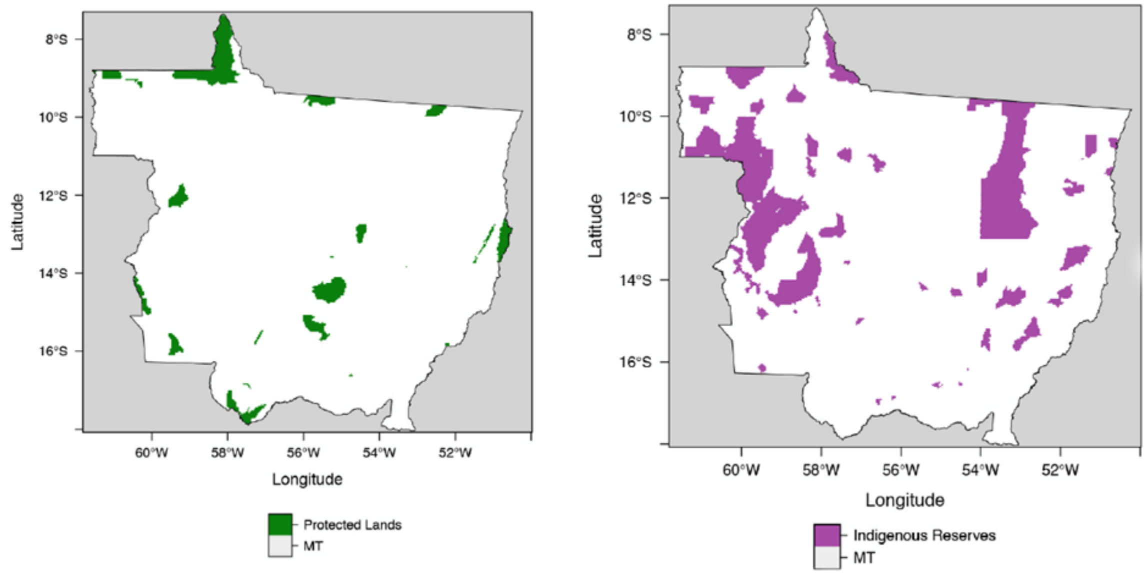

Figure A 2.4. Protected Areas. At left are protected areas in 2012/13 and at right are indigenous reserves in 2012/13.

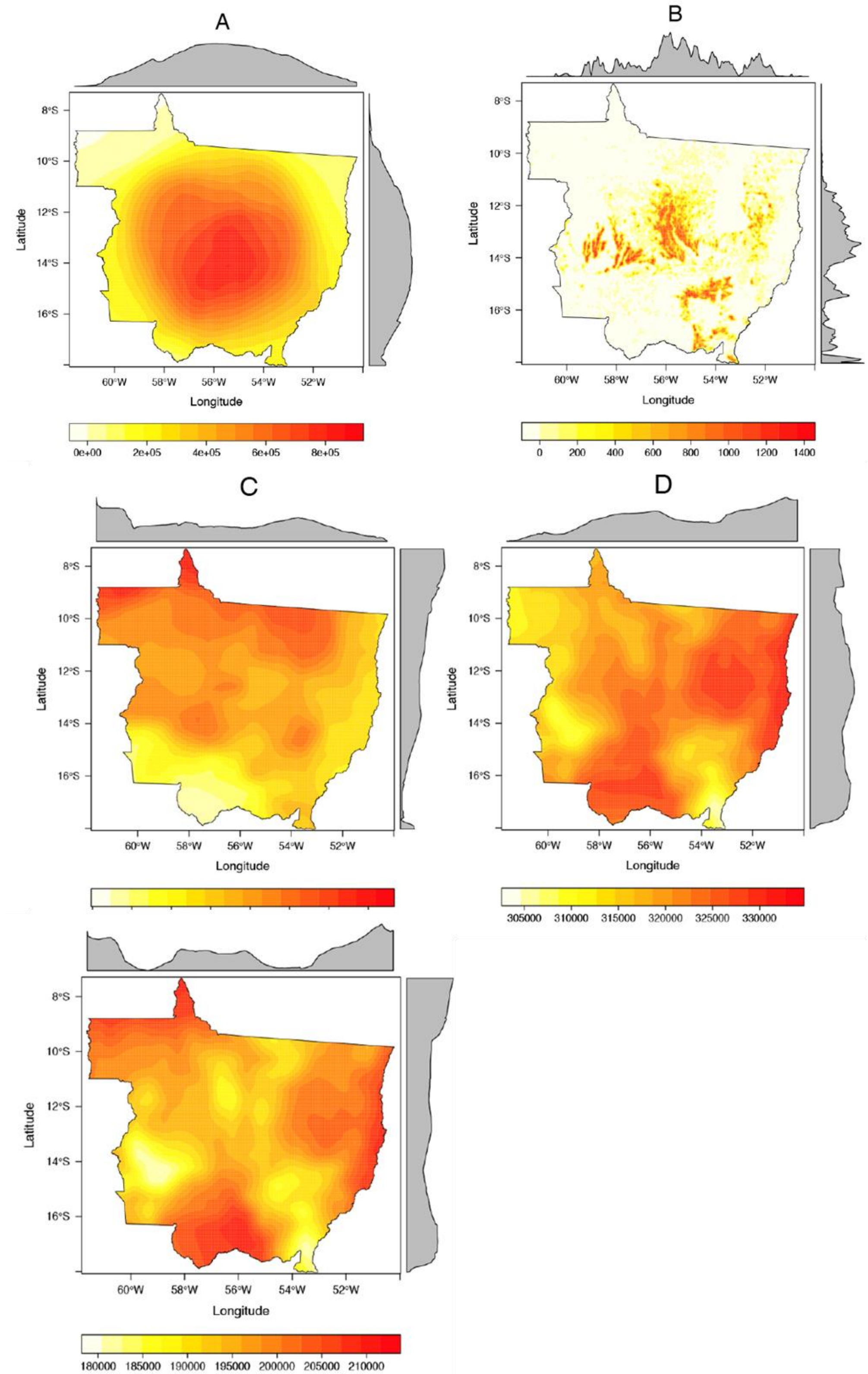

Figure A 2.5. Maps of the spatial control variables. A - ag381km. B -ag5km. C – prec40km. D- tmax40km E-tmin40km.

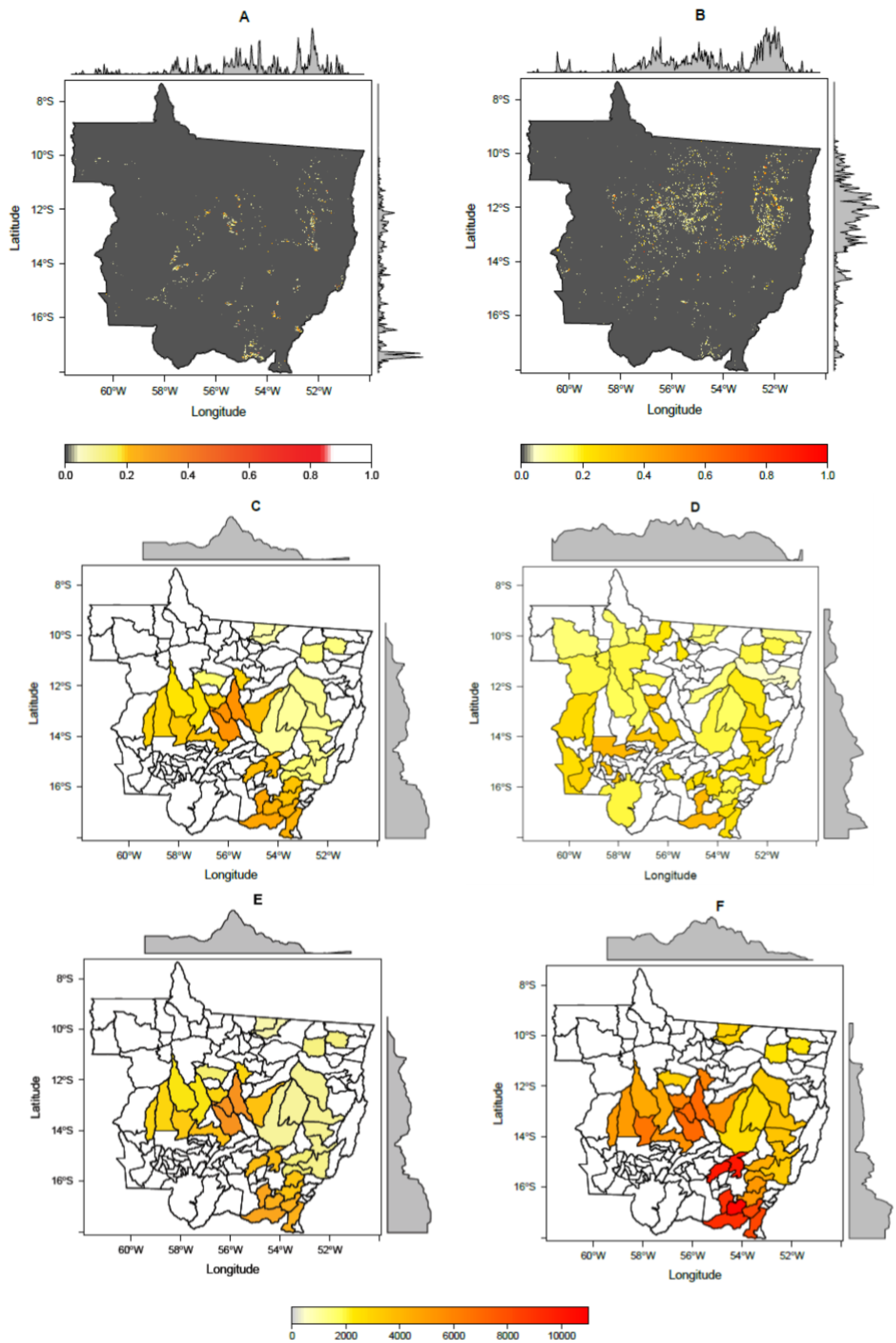

Figure A 2.6. Dependent variables. A- p2c 2002; B- p2c 2013; C- pasture price 2002; D- pasture price 2010; E- cropland price 2002; F- cropland price 2010.

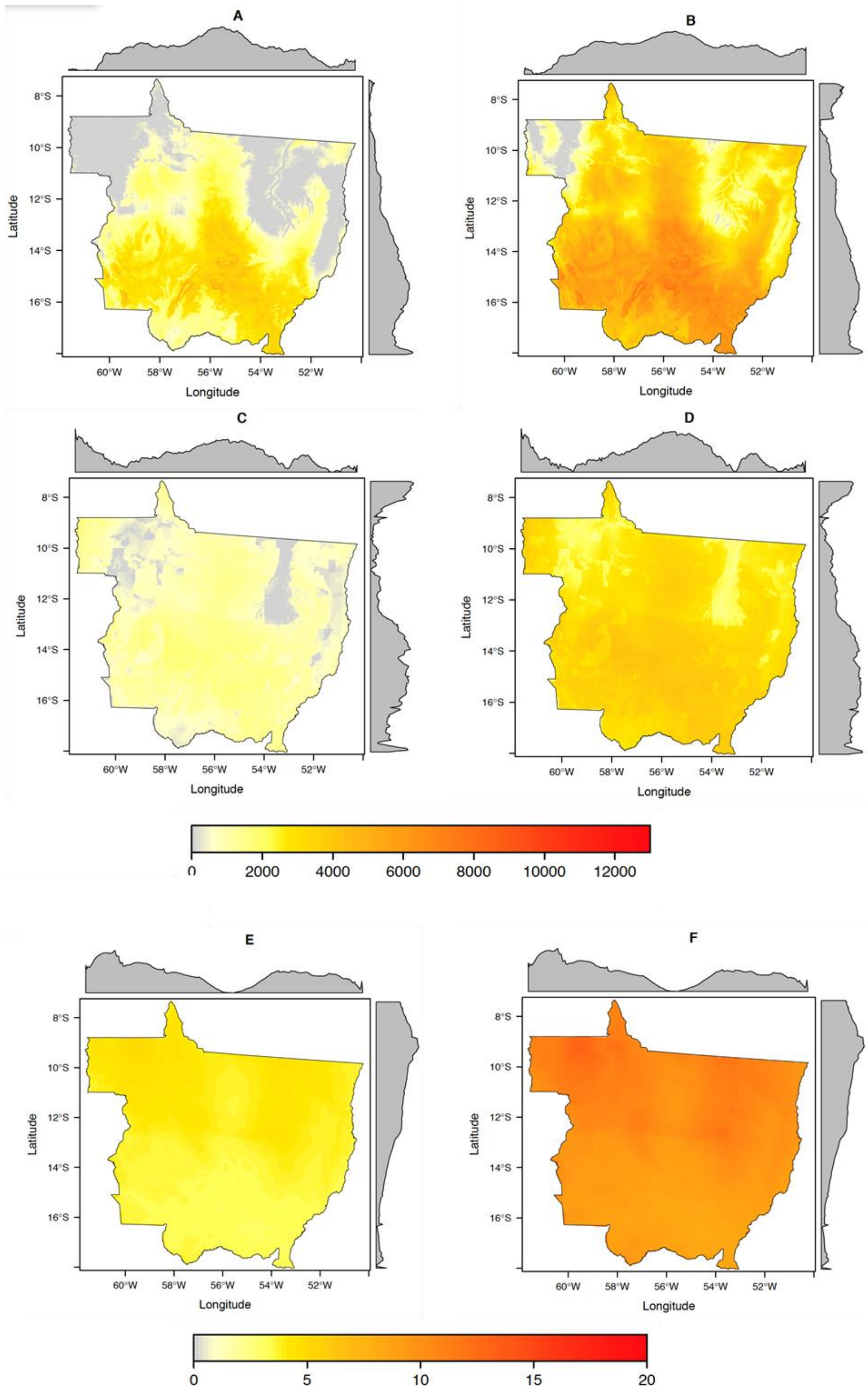

Figure A 2.7. Second stage independent variables. Where A-croppricepr2002 B-croppricepr2013 C-pastpricepr2002 D-pastpricepr2013 E-convint2002 F-convint2013.

Table A 2.9. Moran's I test. I is Moran's index of spatial autocorrelation; E(I) is the expected value of the index under the null hypothesis of no spatial autocorrelation, and sd(I) is the standard deviation of the I.

Variables	I	E(I)	sd(I)	z	p-value*
Precipitation	0.861	0	0.004	230.539	0
Predicted Crop Price	0.865	0	0.004	231.569	0
Predicted Pasture Price	0.896	0	0.004	239.85	0
Temp Max	0.883	0	0.004	236.389	0
Temp Min	0.862	0	0.004	230.705	0
Cropland	0.235	0	0.004	63.011	0
Pasture	0.245	0	0.004	65.592	0

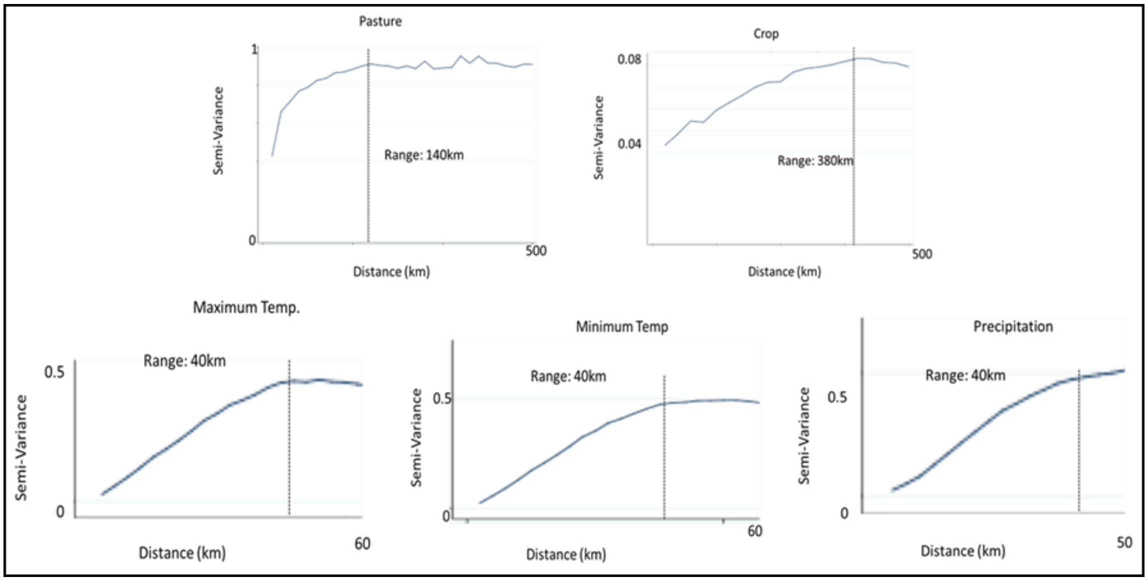

Figure A 2.8. Variograms of pasture, cropland, maximum mean temperature, minimum mean temperature, and precipitation.

*Table A 2.10. T-tests performed for focal municipalities. N is the number of observations (i.e. pixels). Values in parentheses are t-statistics. P-values are indicated as follows: *p<0.05, **p<0.01, ***p<0.001.*

	Soy Transp. Costs		Beef Transp. Costs		Good Soils		N
Juara	0.9	(-.95)	8.394***	(-5.17)	-0.122***	(-7.14)	399955
Vila Rica	3.672***	(-22.69)	23.13***	(-48.45)	-0.190***	(-13.52)	123502
Porto dos Gaúchos	-5.704	(-10.51)	-31.96***	(-20.08)	0	(.)	132040

Table A 2.11. Mean contiguity score of Northeast and rest of Mato Grosso, e.g. the Northeast has a 1.18 times higher incidence of contiguity than the state mean.

	Northeast	Rest of MT
Mean contiguity score (% of MT mean)	118%	41%
Std.Dev.	24%	48%

Table A 2.12. Distribution of P2C by patch size (in percentiles).

	Area (ha)	Cum. Area (ha)
Min.	3.6	1.001
p25	3.9	14 448
p50	7.6	29 288
p75	21.6	71 356
p90	109.6	188 244
p95	269.3	312 885
p99	1.210.4	636 959
Max.	70 010.60	1 228 929
Mean	82.1	-
Std.Dev.	798.9	-

2.9. Appendix 3 – Script used in Focus Groups

1. INTRODUCTION

- Are pastures being converted into cropland? If so, what are the drivers of this process?
- What leads landholders to...
    - Sell their lands?
    - Rent their lands to / from others?
    - Convert their pastures themselves?
- What are the advantages and disadvantages of selling, renting and doing self-conversion?
- How do landholders decide what share of their land to rent to others? Please answer in terms of total size (hectares) as well as proportion of the whole property (%).
- How do landholders decide how much land to rent from others? Please answer in terms of total size (hectares) as well as proportion of the whole property (%).
- How do landholders decide what share of their land to sell to others? Please answer in terms of total size (hectares) as well as proportion of the whole property (%).
- How do landholders decide how much land to buy from others? Please answer in terms of total size (hectares) as well as proportion of the whole property (%).
- What are the characteristics of the land which is converted (incl. size, logistics, infra-structure, soil quality, history of use)? Why?
- Considering the pastures which are converted into cropland, is it correct to say that some have higher chances of being bought/sold, rented/leased, or self-converted? Why?
- Considering the pastures which are sold in Mato Grosso with the specific purpose of P2C conversion, do they have any peculiar characteristic?
- Considering the pastures which are rented in Mato Grosso with the specific purpose of P2C conversion, do they have any peculiar characteristic?

2. THE LAND MARKET

2.1. RENTING (“ARRENDAMENTO”)

- What determines the rental price per hectare?
- Does land rent vary according to location/region? If so, how big is the variation?
- What kind of payment is preferred by the landholder? Why?
- What kind of payment is preferred by the renter? Why?
- To which extent can negotiations between landholders and renters affect the land rent? In other words, which percentage of the rent is up for negotiations between the parties of the transaction? Are prices flexible?
- Besides the price of the rent itself, which other contractual elements are usually negotiated?
- How is contract enforcement ensured?
- Do renters usually require any kind of guarantees? If so, which ones?
- Do these guarantees pose any obstacle / restriction to the establishment of rental contracts?
- How do landholders monitor the activities of renters?

2.2. BUYING / SELLING

- What determines the land price per hectare?
- Does the price vary according to location/region? If so, how big is such difference?
- What kind of payment is preferred by the seller? Why?
- What kind of payment is preferred by the buyer? Why?
- To which extent can negotiations between sellers and buyers affect the price of the land? In other words, which percentage of the final price is up for negotiations between the parties of the transaction? Are prices flexible?
- Besides the price, which other contractual elements are usually negotiated?
- In cases where the payment is done in installments, how is contract enforcement ensured? Are there punishments for breach of contract?
- If the previous answer was "yes", what are these punishments? Do they differ amongst the agents involved?
- Do sellers and/or financing agents require collaterals? If so, which ones?
- If the previous answer was "yes", do these guarantees pose any obstacle / restriction to the establishment of rental contracts?
- How do landholders monitor the activities of their buyers?

3. INFORMATION ON THE LAND MARKET

- Please say what information is most important for producers concerning the decision to engage in a P2C contract.
- In your opinion, what information does the landholder deem as the most important? Is there any difference between those who sell and those who rent out?
- In your opinion, what information do buyers deem as the most important? Is there any difference between those who buy and those who rent in?
- Please list up to 5 additional kinds of information which are important for both sides of the transaction.

4. UNCERTAINTY ABOUT THE LAND MARKET

- When signing a rental contract, what are usual concerns of renters and leasers?
- When signing a selling contract, what are usual concerns of buyers and sellers?
- In cases where the payment is done in installments, do buyers/sellers face any additional concern?
- How do landholders deal with their concerns regarding P2C conversion? Could they take any measures to minimize eventual risks?
- How often do producers get involved in contracts with acquaintances (as opposed to strangers)?
- Do producers usually check the banking records of the other party before they accept to engage in a contract with them? If so, how is it done?
- Does the legal status of the land (esp. land titling) affect P2C adoption?
- How often does land grabbing ("*grilagem*") affect the adoption of P2C contracts?

5. STANDARD CONTRACT

- Please describe a typical P2C rental contract in your region.
- In your opinion, how relevant is the contract duration for the transaction?

- Is it common for producers to take back the land they had rented out before the date specified in the contract – either when that is agreed upon or not?
- In the case of contract breach, what are the consequences for the victim and for the violator?

Table A 2.13. Summary of relevant questions administered to FG participants for the purpose of sample characterization.

Variable code	Question	Answer options	Type
Q2_age	Age	(number) [years]	continuous
Q3_schooling	Schooling	1 = 1/3 basic, 2 = 2/3 basic, 3 = basic, 4 = incomplete high school, 5 = high school, 6 = incomplete graduate, 7= graduate or above	categorical
Q4_birthplace	Birthplace	1 = CO, 2 = SE, 3 = N, 4 = S, 5 = NE	categorical
Q7_migrationyr	How many years in MT?	(number)	continuous
Q9_profile	Respondent's identity	1 = farmer, 2 = rancher, 4 = both, 5 = other	categorical
Q13_experience_yr	Years working in the land	(number)	continuous
Q14a_sizeprop	Property's size (in ha)	(number) [ha]	continuous
Q57_number_prop	How many properties do you have?	(number) [units]	discrete
Q43_affiliation_sum	Sum of affiliations e.g. coop, unions, associations	(score: 1 point per each affiliation type)	discrete
Q44c_private_consultants	Do you have a private consultant?	0 = no, 1 = yes	categ./binary
Q27_p2c_times	How many times have you participated in P2C?	(number)	discrete

2.10. Appendix 4 – Questionnaire used for expert interviews

Study:		Date:				Length of Interview:	

Name:	
Workplace:	
Email:	
Telephone:	

City:		State:	

Interviewer:	

[FILL OUT ALL THE FIELDS ABOVE AT THE END OF THE INTERVIEW]

Hello, my name is _________ from XXX, a market research company in São Paulo that specializes in agriculture and agribusiness. Thank you for having us for this interview. The length of the interview is around 40 minutes and all responses are confidential. Your information will be combined with that of others interviewed. This study is being carried out in four states. For your cooperation, FNP will provide you with its daily bulletins (soybeans or corn) for a period of six months. Are you ready to begin?

E1. Number of interview per state [CIRCLE STATE WHERE INTERVIEWEE IS LOCATED.]

Quota	UF
8	MT
3	MS

Quota	UF
2	S. PA
2	TO

INTERVIEWEE PROFILE

Q1. How familiar are you with the conversion of pasture to cropland in Brazil?

1. ( ) Very familiar
2. ( ) Familiar
3. ( ) Somewhat familiar
4. ( ) Have little familiarity
5. ( ) Have no familiarity [DO NOT CONTINUE.]

Q2. How long have you held your present position?

_______ years _______ months

Q3. What was the location (city and state) of your last three residences and jobs? [LIST MOST RECENT FIRST.]

Table 1. Location of Former Residence and Job

Residences		Jobs	
	Location (City, State)		Location (City, State)
1		1	
2		2	
3		3	

( ) Where I currently live has been my only residence.

( ) My current job has been my first and only job.

Q4. In what area are you familiar with the conversion of pasture to cropland? [CHECK ALL THAT APPLY.]

1. ( ) [IF APPLICABLE:] On your own farm
2. ( ) On your farm and the farms adjacent to you
3. ( ) On farms adjacent to you, but not on your own farm
4. ( ) In the [municipality] where you live
5. ( ) In the [state] where you live
6. ( ) In the Cerrado
7. ( ) In the Amazon biome
8. ( ) In all of Brazil
9. ( ) Other (Please specify.) ___________________

PROCESS AND PARAMETERS OF THE CONVERSION OF PASTURE TO CROPLAND

Q5. Only a small portion of all pasturelands is being/has recently been converted to cropland, and our analysis suggests that pasture to crop conversion is clustered in hotspots.

Q5a. In your opinion/experience what are the determinants of these hotspots? Why are some pastures converted and not others?

[VERIFY THE AREA FROM Q4 HE IS RESPONDING IN REFERENCE TO. CAN BE DIFFERENT FROM WHAT WAS SPECIFIED IN Q4.]: 1 2 3 4 5 6 7 8 9

Q5b. Please rate the importance of the following factors in determining the likelihood/frequency of pasture to crop conversion: [CAN MARK MORE THAN ONE RESPONSE: (EX: SOMETIMES 1 (VERY IMPORTANT), BUT OTHER TIMES 3 (UNIMPORTANT)]

Table 2. Factors in Pasture-to-Cropland Conversion

Factors	1=Very important 2=Somewhat important 3=Unimportant	1=Always 2=Sometimes 3=Never
Soil		
Land Condition		
Proximity to logistics infrastructure		
Land Tenure Status		
Profile of Land Owners		
Land Use History		
Other_________________		

Q6. Who generally participates in pasture-to-cropland conversion? [“WHO”, in the sense of characteristics such as: young vs. old, large vs. small farms, local or NOT, Private individual or CORPORATION.]

[VERIFY THE AREA FROM Q4 HE IS RESPONDING IN REFERENCE TO. CAN BE DIFFERENT FROM WHAT WAS SPECIFIED IN Q4 AND IN Q5.]: 1 2 3 4 5 6 7 8 9

Q7. What is a/some cattle pasture(s) you know relatively well? [EX: PASTURE(S) ON YOUR FARM, IN YOUR MUNICIPALITY, IN YOUR STATE] [write the name/reference of the pasture below. Can list more than one pasture reference:]

Q7a. What percentage of this pasture do you estimate is not suitable for crops?

Q7b. What percentage of this pasture is not for sale at any price?

Table 3. Crop Production Suitability of Pastures and Potential to Sell Pasturelands

Q7. Pasture (Name/Área)	Q7a. % Not Suitable for Crops?	Q7b. % Not for Sale at Any Price?
1.		
2.		
3.		

Why? (Q7b.)

Q8. Through which of the following means have you seen pasture-to-cropland conversion occur? [CHECK ALL THAT APPLY.]

[VERIFY THE AREA FROM Q4 HE IS RESPONDING IN REFERENCE TO. CAN BE DIFFERENT FROM WHAT WAS SPECIFIED IN Q4, Q5, AND IN Q6.]: 1 2 3 4 5 6 7 8 9

1. ( ) Rentals/Leases
2. ( ) Sales/Purchases
3. ( ) Self-conversion
4. ( ) Other 1 (Please specify.) ____________________
5. ( ) Other 2 (Please specify.) ____________________

Q9. Can you estimate as to the share of pastureland-to-cropland conversion that occurs through each channel [CHANNELS MENTIONED IN Q8.] in each of the following states: [ESTIMATE FOR ALL STATES POSSIBLE]

Table 4. Shares of Pasture-to-Cropland Conversion through Different Channels

		2.	3.	4.	5.
State	Rentals/ Leases	Sales/ Purchases	Self-Coversion	Other 1	Other 2
Mato Grosso	%	%	%	%	%
Mato Grosso do Sul	%	%	%	%	%
Tocantins	%	%	%	%	%
Pará	%	%	%	%	%
Cerrado biome	%	%	%	%	%

Q10. [IF CHECKED MORE THAN ONE RESPONSE IN Q8. ASK:] Having seen more than one means of pasture-to-cropland conversion, what do you see as the major differences between the conversion channels [from Q8.]? [Ex: In terms of participants, regions, outcomes, etc.]

Q11. In general, [not necessarily with the specific context of pasture-to-cropland conversion], do some producers prefer to buy or sell vs. rent? If so, why?

Q12. Is the conversion of pasture to cropland constrained by transaction costs? If so, what are the main sources of these transactions costs? [EX: COSTS OF: FINDING/EVALUATING OTHER AGENT IN CONTRACT, ENFORCING CONTRACT, NEGOCIATING CONTRACT, RETRIBUTION IF CONTRACT NOT FULFILLED, FINDING COLLATERAL, MAINTAINING PROPERTY RIGHTS, ETC.]

Q13. [IF INTERVIEWEE MENTIONS THAT CERTAIN TRANSACTION COSTS ARE A CONSTRAINT, ASK:] What is your estimate of these transactions costs? (Please provide a cost range, and in terms of a percentage of total land price.)

Q14. Are you familiar with how pasture-to-cropland rental contracts are structured? Is this in any way different from the typical structure or rental contracts? [RENTAL CONTRACTS MEANING A RENTAL CONTRACT CONDITIONAL ON CONVERSION TO MECHANIZED AGRICULTURAL LAND.]

Q15. What would you say are the most important factors that determine whether a producer engages in a pasture to crop transition rental contract? [EX: price, availability of reliable information on the other agent, type of payment, enforcement of the contract, clear property rights.]

[Please rate all the factors you mentioned, from 1=most important to least important.]

Q16. Does the income of producers affect participation in pasture-to-cropland? [ex: WEALTHIER/POORER PRODUCERS PARCIPATE MORE OR LESS?]

Q17. [IF THE INTERVIEW IS GOING WELL, ASK (INFORMALLY) IF HE HAS AN IDEA OF THE AVERAGE MONTHLY INCOME OF A PRODUCER IN HIS AREA.]

________________R$/month ______________city/region of reference

2.11. Appendix 5 – Results supplement – expert interviews

Table A 2.14. Drivers and constraints to P2C in Mato Grosso mentioned by experts during interviews. Those highlighted in bold were recurrent in all FGs and did not trigger objections from any of the participants. The numbers in the columns on the right-hand side indicate how many times each of the drivers/constraints was mentioned, and those in brackets indicate points on which experts had differing opinions. In the table, we classify drivers and constraints as economic, institutional, demographic, cultural, biophysical, and others. Each phrase is as close as possible to the translation of the direct quotes.

	Category	Subcategory	Fr.
Drivers	biophysical	ensuring that the land is permanently cultivated helps retain water in areas with sandy soils	**2**
		need to restore degraded pasture in order to maintain/increase productivity	16
	economic	P2C is a cheaper way to restore degraded pasture	5
		P2C adds value to the land	1
		land rent (incl. renting and buying operations) is economically attractive	2
		difficulties faced in the cattle sector, cattle prices are low	1
		soybean prices are high, interest in expanding production	7
		producer already farms (in MT or somewhere else)	2
		productive land reduces the incidence of certain taxes ("I.R.")	2
		renting ensures income stability	5
		idle machinery	2
		currency exchange rate (US$ vs. BRL)	1
		integrated crop-livestock systems have environmental and economic advantages	1
		renting allows for checking land quality (and may precede selling)	1
	institutional	stricter environmental regulations made it difficult to open new lands	2
		little support from government to restore degraded pastures (P2C is a cheap option)	1
		social control helps ensure contractual enforcement and reduces transaction costs	1
	demographic	no heir (e.g. due to rural exodus among younger generations)	3
Constr.	cultural	landholder sees himself as rancher (cultural/professional identity + attachment to the property)	1
		ranchers tend to be conservative and skeptical about P2C contracts	2
	technical	**land suitability for farming is limited**	16
		structural changes involved in conversion are often too costly	2
	institutional	buying/selling operations are overly time consuming	1
		transaction costs are high (esp. bureaucratic process)	2
		risk of poor enforcement of rental contracts is high	**1**
		unclear land titling	1
		qualified labor is limited	**1**

Table A 2.15. Experts' opinions on how often and to what degree different factors determine the occurrence of P2C. Numbers indicate frequency of answers.

	Soil/biophysical conditions	Prices	Occupation	LU history	Logistics
Mostly/Always	**13**	**12**	**10**	**5**	**7**
Sometimes	**2**	**0**	**0**	**2**	**1**
Rarely/Never	**0**	**0**	**5**	**6**	**6**

Table A 2.16. Estimates of the share of each P2C pathway by experts from MT vs. other Brazilian states (%).

	Self-conversion		Renting		Selling	
	MT	Others	MT	Others	MT	Others
1	0	74	50	20	50	5
2	20	70	60	25	40	15
3	32	10	40	50	27	40
4	15	15	60	5	25	80
5	-	30	-	40	-	30
6	0	15	60	35	40	50
7	0	-	50	-	50	-
8	20	15	80	15	0	70
Average	12.43	32.86	57.14	27.14	33.14	41.43

2.12. Appendix 6 – Focus groups

Table A 2.17. Characteristics of FG participants according to occupation and participation in P2C.

	P2C participation		Occupation	
	Participants	Non-partic.	Ranchers	Farmers + Both
Ranchers (%)	22%	63%	100%	-
Farmers (%)	33%	0%	-	23%
Both (%)	44%	23%	-	54%
Average age (years)	41	45	43	43
Average schooling (category)	4.89	5.20	5.04	5.15
Birth place - MT (%)	17%	29%	38%	12%
Birth place - other states (%)	83%	71%	62%	88%
Years living in MT	21	21	21	20
Years working in the land	17	16	16	15
Aver. farm size (ha)	1670	3734	3801	2147
Aver. number of farms / person	2.00	1.70	1.85	1.84
Private consultant (%)	39%	40%	42%	38%
Aver. number of affiliations	0.7	1.2	1.2	0.9

Table A 2.18. Drivers and constraints to P2C in Mato Grosso mentioned by local farmers during FGs conducted in Porto dos Gaúchos (PG-1, PG-1), Vila Rica (VR-1, VR-2) and Juara (J-1, J-2). Subcategories highlighted in bold were recurrent in all FGs.

	Category	**Subcategory**	**PG-1**	**PG-2**	**VR-1**	**VR-2**	**J-1**	**J-2**
Drivers	biophysical	pests have reduced ranching revenue	3	2	1			
		burning the pasture, a common measure for pest control, is no longer allowed by law	2	2				1
		need to restore degraded pasture in order to maintain/increase productivity	1	5	1	1	2	4
	economic	**P2C is a cheaper way to restore degraded pasture**	2	3	1	2	3	1
		P2C adds value to the land	1	2	3	2	3	2
		land rent (incl. renting and buying operations) is economically attractive	1	1	(I)	1	3	2
		difficulties faced in the cattle sector, cattle prices are low	2	2		**3**		
		farming is currently more profitable than ranching	2	2	3	3	2	1
		farming is an alternative source of income / allows for income diversification	1	1	1	1		
		farming ensures the feasibility of ranching	3	1	1	2	(I)	(I)
		slaughterhouse monopoly in the region				1	1	
		qualified labor is limited	1	**1**	**1**	1	4	
		integrated crop-livestock systems have environmental and economic advantages	2	1		1	1	1
		good logistics and suitable farm conditions favors the production of grains	1	1	3	(I)	3	4
		low land prices and land speculative interests in the region				**1**		2
		P2C is the only alternative to selling				2		
	demographic	landholder decides to leave the sector			1			1
		no heir (e.g. due to rural exodus among younger generations)			1			
		younger generations (heirs) tend to be more risk prone and willing to do P2C self-conversion						1
	institutional	**social control helps ensure contractual enforcement and reduces transaction costs**	1	2	1	1	2	1
		in case of contract breach, landholder gets some kind of compensation	1	2	2	1	3	3
Constr.	cultural	landholder sees himself as rancher (cultural/professional identity + emotional attachment to the property)	3	1	3	2		
	technical	poor logistics in the region pose difficulties to crop production		1	2	6	2	
		land owner lacks the necessary know-how to start a new enterprise	2	2		2		
		structural changes involved in conversion are often too costly	1	3	1	2	2	3
	institutional	risk of poor enforcement of rental contracts is high	**6**	2		1		**2**
		in case of contract breach, landholder does not get a compensation	1					
		unclear land titling	1	1	2	1	**1**	2
		environmental liabilities exist / compliance with environmental legislation is costly	2	2	**1**	3		
		compliance with labor legislation is costly	2	1			3	
		the region is under embargoe	NA	NA	1		NA	NA
		farmers often prefer renting over to buying in order to avoid land taxes				1		
		access to information on self-conversion is limited	2			1		**1**
	economic	**ranching is less risky than farming from an economic point of view**	1	1	(I)	2	2	2
	others	keeping cattle is used as a way to hide money laundry				1		

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3. Adoption and development of integrated crop-livestock-forestry systems in Mato Grosso, Brazil

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Abstract

By combining crop, livestock and/or forestry activities in the same area, Integrated Systems (IS) can increase organic matter content in the soil – which favors biomass production and allows for higher livestock stocking rates in pasturelands. The implementation of IS is therefore seen as a promising strategy for sustainable agricultural intensification in Brazil, particularly in Mato Grosso state (MT). However, despite the benefits associated with IS and incentives offered by the federal government to stimulate their dissemination, little is known about these systems or the challenges to implement them, and only a limited number of farmers have adopted IS so far. This paper presents a comprehensive assessment of all IS identified in Mato Grosso in 2012/13, which were mapped and described in terms of their main technical and non-technical features. These findings were combined with farm survey data set to provide a detailed account of the various technologies currently being disseminated, their individual diffusion levels and potential adoption constraints. Results generated through qualitative and quantitative research methods give an overview of IS' state of the art, reveal farmer perception of such technology and offer insights into the prospects for low-carbon agriculture in the region. The study's major findings are that IS are present in more than 40 of the 141 municipalities of MT, and the vast majority (89%) involve only crop and livestock. Farmers have adopted three different crop-livestock configurations, depending on their production strategy. Cultural aspects play a major role in farmer decisions to adopt IS, credit provision has not been relevant for IS adoption, and a broader dissemination of IS may occur as land transitions continue.

3.1. Introduction

More than any other country in the world, Brazil faces the challenge of balancing agricultural production and environmental protection. As a major player in the world agricultural market, it is expected to satisfy a significant share of the global demand for food and energy in the coming decades, while also needing to ensure that agricultural expansion will not threaten its forest lands (Nepstad et al. 2009; Godfray et al. 2010; Arvor et al. 2012;). In an effort to prevent further deforestation and optimize land use as a whole, the Federal Government of Brazil is adopting measures to direct the expansion of pasture and crops towards already deforested areas and promote agricultural practices that can intensify production sustainably.

Integrated systems (IS) deserve to be highlighted within this context as a very promising strategy to achieve such goals. By combining crop, livestock and/or forestry activities in the same area, they may be able to increase fertility and organic matter content in the soil. This favors biomass production and allows for higher stocking rates in pasturelands (Bungenstab 2012; Carvalho et al. 2014). Such increase in the system's total productivity represents a direct advantage for farmers if it can be translated into higher economic return and soil conservation over the longer run. In fact, both individual farmers and the society as a whole can benefit from IS given that the maintenance of soil fertility is critical for the conservation of natural resources and provision of environmental services (Lemaire et al. 2014, Salton et al. 2014).

The assessment of indirect impacts of IS adoption is a complex task at the landscape and regional levels, especially when it comes to the prevention of deforestation due to land use intensification in already cleared areas. Most recent studies agree that intensification spares land under certain assumptions (Cohn et al. 2014, Nepstad et al. 2014, Strassburg 2014) and recognize that the effect of agricultural intensification practices (including IS) may differ in frontier regions (Byerlee et al. 2014). Still, the consensus among experts is that IS could help prevent further deforestation (Balbino et al. 2011, Bonaudo et al. 2014).

Integrated systems may include annual and/or perennial crops, different tree species, and several spatial arrangements. Planting densities, field operations and the frequency of rotation between crops and grasses also vary. Such heterogeneity means that farm surveys are not suited to measure the rates at which carbon accumulation occurs in specific IS. Nonetheless, it has already been suggested by literature based on field trials that these systems can contribute to the increase in carbon stocks in the soils (Cerri et al. 2010, Carvalho et al. 2014, Piva et al. 2014, Silva et al. 2014).

When compared with the well-known "agroforestry systems" though, IS usually involve more intense field operations and lower species-diversity. In this sense, IS are relatively similar to conventional agricultural systems in terms of low labor-intensity and high output levels, which makes them a realistic alternative in areas where large-scale commercial agriculture is already in place.

This is the case of Mato Grosso, a Brazilian state lying within the "Arc of Deforestation", where agriculture is rapidly expanding. At the same time, local livestock production systems are highly land-intensive and have low stocking rates, which contribute to increasing overall land pressure and land-use change (IMEA 2010a, Cohn et al. 2011, Alves-Pinto et al. 2013). Considering that Mato Grosso is the main cattle and soya producer in the country and lies adjacent to the densest portion of the Amazon forest, the adoption of IS there could help to achieve both environmental protection and development of more efficient and sustainable agriculture. Additionally, IS could contribute to the rehabilitation of degraded pasturelands, which already accounted for more than 1,6 million hectares in Mato Grosso in 2006 (IBGE) and release carbon into the atmosphere (Silva et al. 2004; Fearnside et al. 2009; Batlle-Bayer et al. 2010; Carvalho et al. 2010).

For all these reasons, IS are one of the six practices eligible for credit under the so-called "ABC Plan" – a major initiative of the Brazilian federal government aimed at reducing greenhouse gas (GHG) emissions from the agricultural sector. Launched in 2010 at the 15th Conference of the Parties to the UN Framework Convention on Climate Change, the Plan is part of the country's National Policy for Climate Change, which sets a voluntary GHG emission reduction target of 36.1 to 38.9% of the total emissions projected by 2020. Specifically concerning IS, the goal is to double the area currently cultivated, reaching approximately four million hectares and preventing the release of about 20 million tons of carbon dioxide equivalent into the atmosphere (CNA 2012).

Still, despite all incentives and benefits associated with IS, adoption by local farmers remains low and use of the credit lines offered through the ABC Plan is still limited. Even though it is important to consider the recent nature of the ABC Plan and to recognize that the number of agricultural loans issued by the banks has increased substantially over the past year, most of these loans are concentrated in Southern Brazil and target practices other than IS (Observatório ABC 2013).

According to the latest official agricultural census (IBGE 2006), only 357,006 hectares were occupied with agroforestry systems in MT (less than 1% of the state's 33,450,060 hectares of agriculture) and official statistics on IS are not yet available. Especially in the state of Mato Grosso, research is lacking on the extent of existing IS, where they are located, their economic and environmental inputs and impacts, and the challenges associated with their implementation.

This paper seeks to contribute to a deeper understanding of integrated systems in Mato Grosso and to offer insights into their potential dissemination by mapping and describing pioneer initiatives, assessing how farmers perceive this new technology and identifying determinants of adoption. It is organized in five sections. Section 3.2 describes the study site and the conceptual framework behind the questionnaire applied to farmers. Section 3.3 presents survey results obtained through the comparison of farmers' socio-economic profiles and the characteristics of farming systems related to all main aspects of the study. These include the IS strategies found in MT, farm and farmer characteristics, soils and other biophysical environmental factors, farmer technological profiles, legal status of the rural property, production data, challenges of IS implementation, credit availability, and farmer exposure to information, . Section 3.4 discusses these results and some policy implications, highlights the impacts of IS on the environment (and vice-versa) as perceived by farmers, and then answers whether any of the factors listed above represents a barrier to a broader dissemination of IS and/or to the consolidation of low-carbon agricultural systems in the region. Finally, Section 3.5concludes the discussion and highlights further research venues on integrated agricultural systems that were identified with the study.

3.2. Material and methods

Since specific IS data are not yet available, we initiated the study by identifying all IS adopters in the state of Mato Grosso by contacting unions, professional associations, rural extension services and consultants in every municipality of Mato Grosso state. A comprehensive questionnaire was designed and pilot-tested together with local experts, and then administered to both IS adopters and non-adopters (all interviews were conducted by the first author). Networks of trust had to be developed in order to access sensitive and/or confidential information on land tenure, credit and environmental liability issues. Such data are often unavailable due to their strategic nature or even because they reveal poor law enforcement.

All four types of IS defined in the "National Policy for Integrated Crop-Livestock-Forestry

Systems”, established by the Federal Law n. 12805/2013, were considered for this study:

- iCL – Crop-livestock systems (i.e. integrated production of grains, grasses and animals);
- iLF – Livestock-forestry systems (i.e. integrated production of grasses, animals and trees);
- iCF – Crop-forestry systems (i.e. integrated production of grains and trees); and
- iCLF – Crop-livestock-forestry systems (i.e. integrated production of trees, grains, grasses and animals).

In order to assess the influence of biophysical environmental factors on the adoption of IS, quantitative data were collected on the location of farms using IS, and qualitative data were collected within those farms on locations where IS were more likely to be practiced. In both cases, this evidence was reported by farmers themselves, based on questions about whether they thought that the soil on their properties was adequate for the cultivation of certain species, as well as whether IS would be an interesting option in selected locations.

The assessment of the influence of IS adoption on the biophysical environment, on the other hand, is less straightforward. As most integrated systems are new in Mato Grosso, treatment/control evidence of their environmental impacts is still lacking. Nevertheless, data on before/after management practices of farms were collected where IS are adopted and not adopted (including information on stocking rates and basic field operations, e.g. fertilizer applications). As already mentioned in the introduction, the literature contains strong evidence linking several of these management practices to environmental outcomes (such as their impact on water pollution, GHG emissions, etc.), but exploring those is beyond the scope of this paper.

3.2.1. **About the study site**

Mato Grosso is the third largest state in Brazil (906.806 km^2) and corresponds to 10.61% of Brazil’s total area. It has 141 municipalities. The climate is characterized by a dry season (May-September) and a rainy season (October-April) over which rainfall patterns vary from 1200 to 2000mm. Latossols predominate in the region, followed by Podzolic soils and sandy soils (Embrapa 2006). Mato Grosso contains parts of three highly biodiverse biomes (i.e. Pantanal, Cerrado and the Amazon rainforest) within which landowners must set aside 20-80% of their properties for environmental conservation under the Brazilian Forest Code.

Mato Grosso’s economy has been very much oriented to large-scale commercial agriculture since its colonization back in the 1970's and 1980's, when the federal government offered incentives for land occupation (Arvor et al. 2012). For this reason, average property size is over 5,000 hectares, land concentration indexes are high and a handful of agricultural products comprise most of the state revenue – particularly soya, maize, cattle, cotton, and sunflower (IMEA 2012). Most of the medium and large holdings in Mato Grosso are dedicated to the first three enterprises, particularly for the production of beef and soy beans (maize is a typical second harvest). However, crop farmers and livestock producers in the state greatly differ in terms of risk-aversion, investment profile and cultural identity.

Livestock farming accounts for the largest portion of agricultural land use in Mato Grosso – approximately 29 million hectares (IMEA 2012). Most farm holdings operate at a rather low technological level, are not highly capitalized and rarely incorporate best management practices. Cattle are raised free-range and extensively, pastures usually have a low carrying capacity and average stocking rates are low. The initial investment required is practically equivalent to the acquisition cost of land and cattle; management techniques are simple (little specialized knowledge is required) and the fact that opening new areas for the implementation of pasturelands often followed selective logging usually means that the money obtained through the trade of timber can provide the initial capital for the activity. The highest cost of production corresponds to the restoration of degraded pastures, for which purpose farmers usually grow rain fed rice for some years. Cattle production also involves minor constraints in terms of liquidity, and requires rather limited financial resources per hectare of land. In fact, livestock farming sustains itself on large-scale holdings – large herds on large farms – despite the generally low productivity indicators found in MT (IMEA 2010a).

On the other hand, soybean production covers a much smaller share of the state's land resources (7,914,088 million hectares in 2012/13) (IMEA 2012). Yields tend to be high and these production systems are quite intensely managed. According to the Brazilian National Supply Company (CONAB 2014), productivity in Mato Grosso has been superior to the national average productivity since 1980 for several agricultural products including soya. As the latter requires regular precipitation and flat areas for mechanization, soybean farming is usually located where land prices are highest; moreover, the fact that producers need to reach a certain scale to be competitive in the market implies that the initial investment is much higher in this sector than in cattle production. The level of technical expertise and education is equally higher among soya producers, and besides being culturally open to technical innovations, they tend to be risk-prone (many take credit from banks and from traders, whom they commonly set up future contracts with).

3.2.2. **Sampling procedure**

The so-called "5-step sampling procedure" (Henry et al. 2003) served as guideline for the present study. Initially, all identifiable IS were mapped through interviews per telephone and e-mail. Approximately half of them were randomly selected for in-person interviews according to the stratified random sampling technique (Daniel 2012), so as to ensure that each of the four types of IS (iCL, iLF, iCF and iCLF) are represented proportionally to their occurrence in Mato Grosso state.

The selection of IS non-adopters was carried out in the same municipalities of the selected IS adopters as a way to reduce the standard deviation of answers collected within each stratum and elicit other characteristics of interest. Priority was given to specialized soya producers and specialized cattle producers whose properties were situated in the same or adjacent municipality; whenever that was not possible, producers were selected so as to be based on the same macro region (IMEA 2010b). Their contacts were taken from a list of all farm holdings derived from the agricultural census and completed with additional and updated information obtained from the Federation of Agriculture and Livestock of the State of Mato Grosso.

In total, interviews comprised 61 IS adopters and 73 non-adopters (of which 41 were specialized soya producers and 32 were specialized cattle producers). In order to get a general overview of the quantitative data collected, basic statistical analyses were performed between adopters and non-adopters. Graphs were made for each population individually (i.e. IS adopters, specialized cattle producers and specialized soya producers) so as to check for differences related to each of the main variables tested in the survey (see Appendix 1).

3.2.3. **Conceptual framework**

Literature on technology adoption often looks at adoption determinants from the perspective of inherent characteristics of the technology under study (including cost, complexity, risk, stability and profitability) (Batz et al. 2003; Lee 2005; Engler-Palma and Hoag 2007). Even though such an approach could also be applied to the agricultural, livestock and forestry sectors, it is important to consider biophysical factors, attitude towards environmental conservation and certain risk preferences individually, so as to account for the full extent to which they may drive farmers' attitudes.

With that in mind, the questionnaire design was based on the conceptual framework of Pattanayak et al. (2003). Attempting to take stock of several empirical studies published over the past years on agroforestry adoption, the authors of this framework suggest five general categories of adoption determinants:

- Personal preferences (which encompasses elements such as farmer risk tolerance, conservation attitude and intra-household homogeneity, and is measured through socio-demographic proxies like age, education and social status);
- Resource endowments (which measure the resources available to the technology adopter for implementing a new technology, i.e. assets holdings such as land, labor and savings);
- Market incentives (e.g. prices, access to markets, transportation and potential income losses and gains);
- Bio-physical factors (e.g. soil quality, slope of farmland, plot size, etc.);
- Risk and uncertainty (which reflects the unknown in the market and institutional environment under which decisions are made, such as fluctuations in commodity prices, projected output and rainfall).

Additionally, the present study assessed factors such as producer legal status, eligibility for credit and access to information and communication channels. It also combined cross-sectional data analysis with open-ended questions and expert interviews. Finally, considering that "farmers make their decisions on land use in light of their own objectives, production possibilities and constraints, understanding their incentives is essential to understanding patterns of resource use and to formulating appropriate responses to problems" (Current et al. 1995), this study emphasizes producer perceptions of advantages and disadvantages of IS at the farm level (and on particular plots within farms, where applicable)rather than the technical accuracy of their answers.

3.2.4. **Data sources**

Primary data were obtained through a survey with 134 farmers, workshops and meetings with experts during a 6-month field research period. Secondary data were either taken from the scientific literature or from other studies conducted by local organizations – including FAMATO, APROSOJA, ACRIMAT, FASE, IMEA, UFMT, Embrapa Agrossilvipastoril, INPE, non-governmental organizations involved in the establishment of ABC Plan at the state level (IPAM, ISA, TNC), EMATER (rural extension), Secretariat of Agriculture, Secretariat of Environment and unions. Entities located in other parts of Brazil were also contacted, such as the Secretariat of Agricultural Development and Cooperativism (SDC – MAPA), EMBRAPA's head office in Brasília, Ministry of Environment and financing institutions (BNDES, Banco do Brasil and Rabobank-Brazil).

3.3. Results

Existing integrated systems were identified in 29 of the 141 municipalities of Mato Grosso. They are mostly concentrated around the municipalities of Sinop (36), Tangará da Serra (9) and Canarana (11), as depicted in Figure 3.1:

1	Água Boa
2	Alta Floresta
3	Alto Garças
4	Alto Taquari
5	Araputanga
6	Barra do Garças
7	Brasnorte
8	Cáceres
9	Campo Novo do Parecis
10	Campos de Júlio
11	Canarana
12	Cláudia
13	Cuiabá
14	Feliz Natal
15	Gaúcha do Norte
16	Guarantã do Norte
17	Guiratinga
18	Itaúba
19	Jaciara
20	Juara
21	Lucas do Rio Verde
22	Marcelândia
23	Nova Canaã do Norte
24	Nova Guarita
25	Nova Mutum
26	Nova Xavantina
27	Peixoto Azevedo
28	Porto dos Gaúchos
29	Primavera do Leste
30	Querência
31	Rondonópolis
32	Santa Carmem
33	Santa Rita do Trivelato
34	Santo Antonio do Leverger
35	Sapezal
36	Sinop
37	Sorriso
38	Tabaporã
39	Tangará da Serra
40	Tapurah
41	Vera

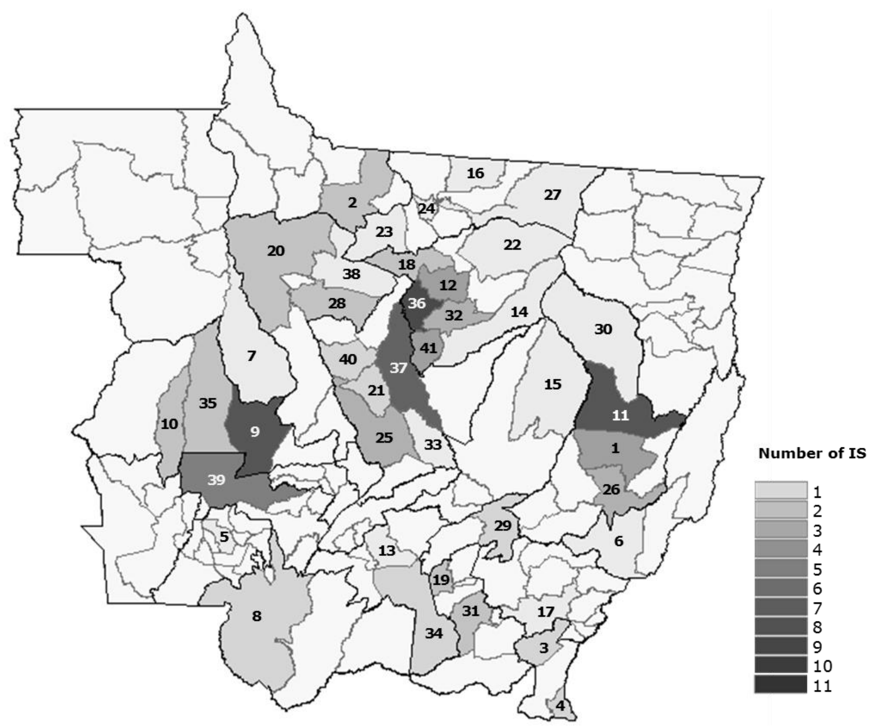

Figure 3.1. Distribution of IS per municipality in Mato Grosso, Brazil (2012/13)

The total area under ISs is estimated to be around 500,000 hectares. Total farm size of IS adopters is 3,936 hectares in average, and usually 30% of their property is allocated to IS. As depicted in Figure 3.2, crop-livestock systems (iCL) are the most common type of IS in Mato Grosso (89%), followed by livestock-forestry (iLF) and crop-livestock-forestry (iCLF) – 5% each. Crop-forestry systems (iCF) corresponded to only 1% of the interviewees.

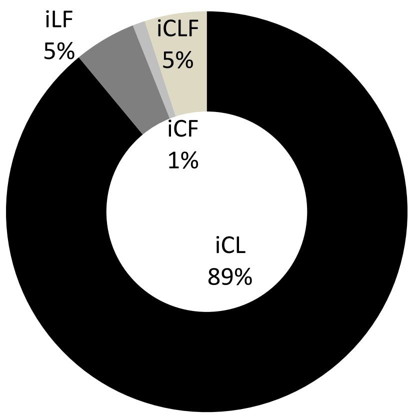

Figure 3.2. Major types of IS identified in Mato Grosso (2012/13)

3.3.1. **The different iCL strategies**

The population of IS adopters was found to be quite heterogeneous. Integrated crop-livestock systems, in particular, may have different configurations depending on the farmers' production strategies. The three most common configurations found during the study are explained as follows:

- *iCL1 – "Rotation":* Crop and livestock production are equally important in this configuration, which explains why the plots dedicated to each of the two usually have the same size. Ex.: The farm is divided into plots 1, 2, 3 and 4. For two years, plots 1 and 2 are dedicated to crops while plots 3 and 4 are dedicated to pasture. In the following 2 years, plots 1 and 2 will be dedicated to pasture while plots 3 and 4 will be dedicated to crops. The rotation is continuous, but the number of plots and the frequency of rotation may vary depending on the farmer's possibilities and preferences.

- *iCL2 – "Rehabilitation of degraded pastures":* This configuration is focused on livestock production. The idea is that the farm is almost entirely dedicated to pastures and only a smaller plot is set aside at a time, so as to have its fertility restored by the rotation with crops (agriculture requires the application of fertilizers, so this activity shift helps replacing fertilizers that have been lost). Considering the same hypothetical farm used to exemplify the first case (iCL1), this time only plot 1 would be dedicated to crops while plots 2, 3 and 4 would be dedicated to pasture. After a year, plot 2 would be dedicated to crops, while the others would be dedicated to pasture; after one more year, plot 3 would be dedicated to crops while the others would be dedicated to pasture; and so on. Once again, the number of plots and the rotation frequency may vary.

- *iCL 3 – "Off-season cattle":* The focus of this configuration is agriculture, specifically soya and second-harvest maize. Once soya is harvested, maize is planted together with grass (in parallel lines). Maize grows faster and it is harvested first; once that happens, the grass starts receiving more sun light and developing faster. Cattle are then introduced around May/June and remains in the area during the entire dry season (until September/October). Such shift between crop and pasture enhances soil fertility and biomass production – particularly during a period when stocking rates are considerably lower in traditional farming systems – and optimizes the use of land and other resources throughout the year. This configuration is considered the most sophisticated one in terms of management, given that maize and grass must be planted simultaneously and harvested at different times.

It is important to clarify that the correspondence between strategy and configuration is not always straightforward, since different configurations may fulfill the same strategy. For instance, both iCL1 and iCL2 adopters wish to diversify their production while, at the same time, promote soil fertility; what makes them chose between one or the other is basically the level of soil degradation on-farm, as well as the possibility/willingness to bear with the additional costs of crop production.

What our study also shows is that, in most cases, farmers seem to adopt iCL1 as a preventive measure against soil degradation and iCL2 as a remediation measure whenever degradation is already occurring – but there is no agreement about the level of soil degradation that requires any action, and this could vary according to market conditions, too (e.g. even after identifying the need to apply fertilizers to the pasture, a farmer may decide to postpone it if fertilizer prices happen to be too high). Combined with the fact that a farmer's production strategy is dynamic (it may change according to prices of inputs and outputs, for example) these factors make it hard to quantify farmers according to the configuration adopted. However, when asked about the major motivations for iCL adoption, "rotation" was mentioned by most of the respondents (67%), followed by "rehabilitation of degraded pastures" (57%) and "off-season cattle" (32%) – which shows that integrated crop-livestock systems are often used with the purpose of ensuring soil fertility.

3.3.2. **Farmer characteristics**

All respondents were men and owned the farms themselves. No significant difference concerning average level of education attainment (measured in years of formal education) was found among IS adopters nor between them and specialized soya producers; however, the same indicator for specialized cattle producers was slightly lower. The fact that approximately 70% were born in Southern Brazil and migrated to Mato Grosso in the 70's and 80's is likely related to the low number of farms with forestry activities, reflecting the Southern tradition of producing grains for exports. In fact, most migrants were attracted by the idea of economic prosperity advertised by the government, and received incentives to suppress the natural vegetation as a way of ensuring the ownership to land.

The factor "ownership of other farms", taken as a proxy for financial resources, was considerably higher among IS adopters (Figure 3.3). Along the same lines, statistical analyses showed that IS adoption was 3.3 times higher among respondents with an additional income source than among those without (see Appendix 1).

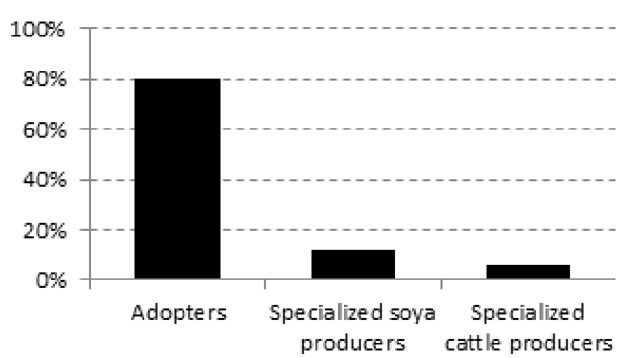

Figure 3.3. Ownership of other farms among respondents

3.3.3. **Farms characteristics**

No property under 1000 hectares was found among IS adopters, except for one case in the city of Sinop. However, smaller properties (i.e. less than 300 ha) represented 27% of the cases among non-adopters, supporting expert opinion that IS are more prone to be adopted by larger farms due to their high investment costs. On the other hand, looking at the correlation between property size and some other variables such as education level and access to communication channels, we see that size itself is not much of a determining factor for the adoption of IS but rather a reflection of all these other variables. In fact, even though it is hard to establish a clear causal relationship between these elements, there is no doubt that IS have been more widely adopted in larger farms so far.

The ratio between productive area and total area was lower for IS adopters, meaning that a larger share of their properties was left uncultivated. The uncultivated land usually corresponds to Permanently Protected Areas ("APP") and Legal Reserve ("RL"), two policy instruments for environmental preservation contained in the Brazilian Forest Code. The Code requires "set-aside land" (whose share ranges from 20% to 80% of the total property area depending on the biome where the property is situated).

Farmers were also asked about biophysical characteristics of their farms. Moreover, IS adopters were asked whether any of those characteristics influenced their choice of where to implement IS within the farm and, furthermore, which of the three iCL configurations to adopt (if applicable). Table 3.1 summarizes the answers given by IS adopters, specialized farmers and specialized ranchers (expressed as a percentage of positive responses out of the total number of observations). As depicted, the presence of rocky soils is more common among ranchers than the other two groups (19%), which makes sense considering that rocky soils may impede mechanized operations. Almost none of the specialized farmers reported soil compaction (2%) whereas a much higher number of IS adopters and specialized ranchers did (16% and 25%, respectively), probably because of the presence of cattle. No aridity was reported. Acidity was reported by all three groups as equally severe, whereas the occurrence of erosion was slightly lower for specialized farmers than IS adopters and specialized ranchers (5% compared to 10% and 9%, respectively).

Table 3.1. Occurrence of selected farm biophysical characteristics by group of respondents (%)

	Rocky soils	Acidity	Sandy soils	Soil compaction	Aridity	Erosion
IS adopters	8%	54%	36%	16%	0%	10%
Spec. farmers	0%	55%	15%	2%	0%	5%
Spec. ranchers	19%	53%	22%	25%	0%	9%

The occurrence of sandy soils in farms with IS was more than double the occurrence of sandy soils in specialized farming systems (36% and 15%, respectively). Further statistical tests performed with the variable “s2sand” show that the odds of IS adoption were higher in the presence of sandy soils (see Table A 3.1 in Appendix 1). The Chi-square and Fischer’s exact tests performed for discrete variables showed that there is an association between “presence of sandy soils” and IS adoption (which is consistent with the previous results), as well as no association between “topography” and IS adoption (see Table A 3.2 in Appendix 1).

During the research, some producers reported that they chose to allocate marginal parts of their properties to try out IS. Others mentioned that the rotation of crops and pasture improved farming conditions where soils were too sandy (and, thus, not perfectly suitable for soya cultivation) because the deep root system of some grasses helped structuring the soil. However, as these subsamples were so small (and only 6 producers had forests, for example), robust statistical analyses to test for the association of biophysical factors and the adoption of specific IS types/configurations could not be performed.

In terms of land ownership, results show that IS adopters have less land rental contracts than non-adopters, and that IS were usually implemented in privately owned lands. Qualitative data collected throughout the survey confirmed that farmers tend to feel more comfortable undergoing long-term investments in their own lands (for instance, when it includes the rehabilitation of degraded pasturelands or the cultivation of trees). It was also found that IS were usually implemented by individual farmers, whereas investment groups usually opt for traditional systems that were already well-established practices and yield immediate profit – especially when compared to IS that included forestry activities.

Finally, the average number of staff members per hectare was higher among IS adopters. However, when asked about the need to hire new employees for the implementation of IS, interviewees rarely answered that it was necessary to do so. These two results combined suggest that IS were usually implemented by farmers who already had more employees (which might be due to the fact that IS are generally more labor-intensive). They also confirm that the adoption of a new technology always implied some risk and should be constantly monitored (in fact, a farmer would be unlikely to start a new management regime unless a minimum number of employees were available to correct eventual problems and adjust the new system if necessary).

3.3.4. Farmers' technological profile

Almost all IS adopters and specialized soya producers make use of technologies such as soil analysis, minimum tillage, transgenic seeds and precision agriculture (with no statistically meaningful difference between the two). Cattle producers, on the contrary, have a comparably less "high-tech" profile, which is in line with other factors that indicate they are risk-averse and do not have the same willingness to invest in innovations.

3.3.5. Legal status of the farm

The vast majority of interviewees holds the title of the land and has not faced any conflicts or disputes over the land in the past 15 years, attesting the importance of tenure security for the establishment of any of production systems. When asked if their properties are registered in the Brazilian Rural Environmental Registry "C.A.R.", 73% of all interviewees said that their current legal situation is either regular or in the process of being regularized. There is, however, a clear disparity between the share of the land that should be set aside according to the legislation, and the area declared as "non-productive" by respondents. Even assuming that such difference is being compensated though the preservation of areas outside the farms – an element of the recent revisions to the Brazilian Forest Code – it is neither possible to check for the validity of the answers nor to draw conclusions from them. Yet, statistical analyses showed no association between the C.A.R. registration and IS adoption (see Appendix 1).

3.3.6. Conventional vs. integrated production

The rate of carbon accumulation in soils under IS and the consequent increase in biomass and productivity depend on a number of factors, such as farm characteristics (e.g. soil type), the IS implemented (e.g. rotation frequency, species used, planting density, etc.) and field operations. As revealed by this research, farmers tend to implement IS in different ways; for instance, the rotation frequency between crop and pasture ranges from two to five years, and may change in the future according to farmers' preferences and possibilities. Together with the fact that almost all identified IS are not older than two and a half years, and thus have not yet reached stability in terms of microbiotic activity and organic matter increment, these factors make it still extremely hard to calculate an average rate of carbon accumulation in the soil. Besides, this process depends on the synergistic effects between crops, livestock and forestry – and the data collected so far, under Mato Grosso agro-climatic conditions, are limited.

Yet, data on before/after management practices collected in conventional and integrated systems offer evidence of positive environmental impacts of IS in terms of carbon accumulation. The fact that IS are often associated with low-carbon conservation practices such as minimum-tillage also supports that conclusion. Even though market prices received for soya, maize and cattle are the same under integrated and conventional farming systems, average productivity reported by IS adopters was similar to that of conventional systems for both crops and trees and about three times higher for cattle (the average stocking rates for farms with and without IS were 3.4 and 0.98 animal units/hectare). Many respondents also reported better pasture conditions, not only in terms of grass production (i.e. higher biomass productivity) but also in terms of the persistence of the production also during the dry season, when the carrying capacity of conventional pastures would normally drop and cattle would lose weight. Instead of grazing for about 3.5 to 4 years as in conventional livestock production systems, some IS adopters said that their cattle reached slaughter weight after 3 years on average. By shortening the life cycle of cattle, IS also contribute to minimizing methane emissions and mitigating climate change.

Some iCL adopters reported a reduction of their expenses with fertilizers (about 15% below the average in conventional systems), feed (since crop residues left on the ground can be consumed by the cattle), and fodder (especially for ranchers who introduced cropping systems and now have the option of producing their own hay/silage instead of purchasing from a third party). Some interviewees said that the straw left on the ground helps inhibiting the emergence of weeds in the pasture, but none could provide figures indicating the extent to which that really helps. Most also cited IS' ability to promote income diversification as an advantage, which helps reduce farmer exposure to market fluctuations and unfavorable climatic conditions.

During the survey, a few producers mentioned the need for additional field operations able to reverse the soil compaction caused by cattle before planting crops. Some also expressed concerns about the impacts that the shade of trees could have on crop productivity, or how pest cycles would be affected by rotation. Yet, their perception of IS was generally positive, as discussed in detail in section 3.3.9.

3.3.7. **Integrated systems in place**

According to the survey, a limited number of species of crops, grasses and trees (approximately 12) were used across all existing IS, despite the flexibility of integrated systems. They also have similar rotation frequencies of every two years between crop and livestock activities, on average. In terms of machinery and labor requirements, IS are comparable to conventional systems but productivity differs between them, as mentioned above.

Most IS adopters ranked the reasons that led them towards IS as follows (starting from the most important): "potential higher income", "production diversification", "possibility to rehabilitate degraded pasturelands", "potential decrease of input costs" and "improvement of environmental conditions in the farm as a whole".

Concerning the modifications necessary for the implementation of different IS and the costs associated to each transition pathway (from conventional to integrated farming), it is notable that the introduction of forestry entails the highest costs, followed by the introduction of crops and then livestock. In fact, soya farmers who decided to introduce cattle in their properties (16 observations) had to invest only in minor structural adaptations, such as the construction of fences and water pumps. On the other hand, almost all farmers who introduced crops (21 observations) had to invest in major modifications, including the application of lime for soil pH correction, acquisition of specialized machinery, etc. Farmers who already conducted both crop and livestock activities before implementing rotation (15 observations) had only minor costs related to farm management (e.g. rearrangement of task divisions and work plan); however, those introducing forestry activities (6 observations) faced the highest adaptation costs due to specialized machinery requirements. Farmers from the first two groups (i.e. who introduced livestock/crop) often adopted IS exactly because idle machinery was already available and their original farm configurations were naturally suitable for rotation schemes.

Figure 3.4 ranks farmer motivations for implementing IS in the vertical axis and shows an interesting correlation between motivations and the transition they underwent (represented by the different colors of the horizontal bars). Results are depicted in number of cases captured in the survey. As already introduced in Section 3.3.1., most respondents answered the combination of rotation and rehabilitation of degraded pasturelands (a), followed by rehabilitation only (b), rotation and off-season cattle (c) and so on. For instance, looking at bar "e", it is possible to infer that farmers intending to promote off-season cattle used to be specialized crop producers and opted for introducing livestock in their original system; bar "c" shows that all farmers who mentioned the promotion of *rotation* and *off-season cattle* as motivation factors to start IS used to be specialized crop producers and decided to introduce livestock; the two first bars reveal that most of the farmers who started IS with the purpose of promoting both *rotation* and *rehabilitation of degraded pastures* (a) or only *rehabilitation of degraded pastures* (b) used to be specialized cattle ranchers and decided to introduced crops in their original systems.

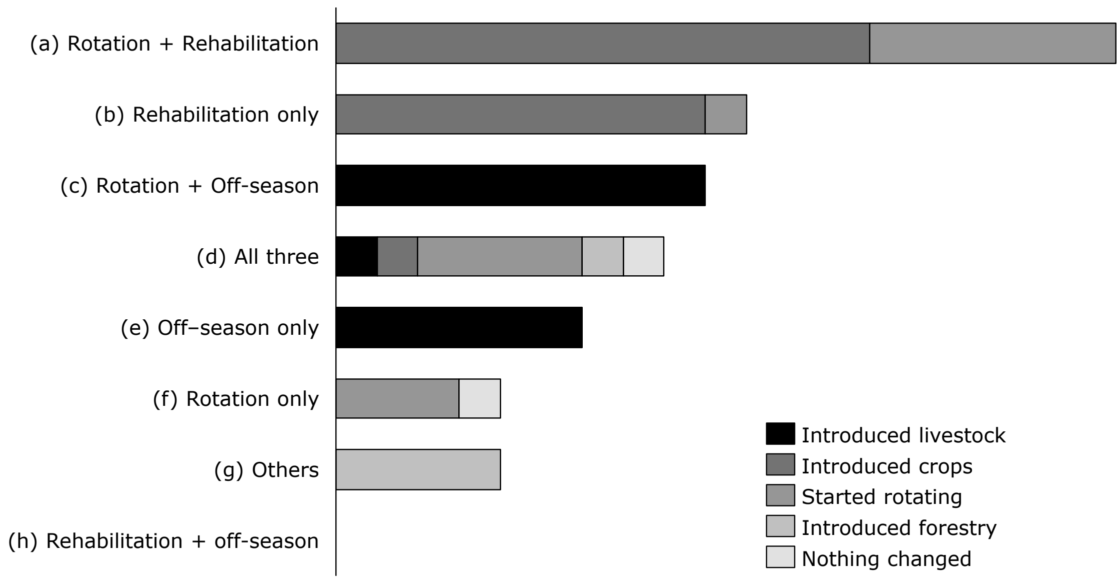

Figure 3.4. Combination between strategies and transitions among iCL adopters

3.3.8. **Challenges in implementing IS**

In an attempt to assess the difficulties and challenges of implementing IS, both adopters and non-adopters were asked to rate eight selected factors: i) know-how and technical knowledge; ii) management complexity; iii) machinery; iv) implementation costs; v) maintenance costs; vi) labor needs; vii) commercialization; and viii) the purchase of tree seedlings for farmers dealing with forestry activities. In the case of IS adopters, a grade from 1 to 5 (as depicted above the bars) was supposed to express the degree to which each factor represented a challenge throughout the actual process of IS implementation; in the case of IS non-adopters, it expressed their opinion on the extent to which each of the factors would be a challenge if they were to implement IS.

Overall, “labor”, “implementation costs” and “know-how” were the factors that had the highest grades, as depicted in Figure 3.5; for those implementing forestry activities, “implementation costs” and “commercialization” were the most important ones. It was interesting to notice that producers who initiated IS a few years earlier than others attributed a comparatively higher grade to “know-how”, suggesting that the knowledge on IS is spreading and pioneer initiatives serve as models for later IS adopters. Finally, some of the grades given by non-adopters to technical factors were higher than those given by those who have really been through the implementation process. Considering that these farmers have similar socio-economic conditions, such disparity suggests cultural resistance and skepticism towards new agricultural practices.

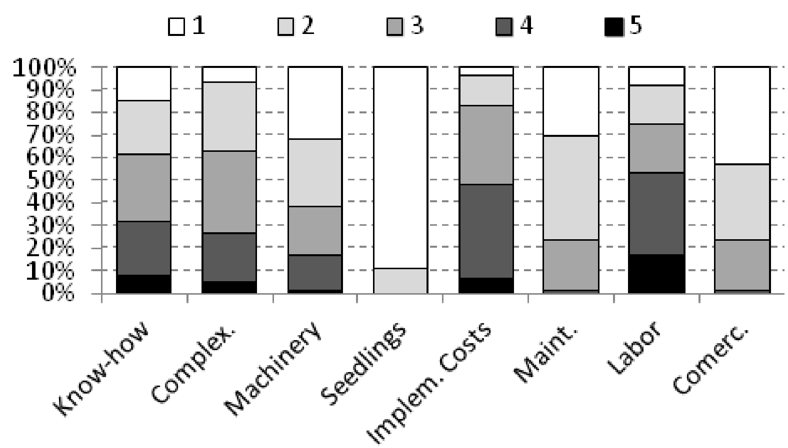

Figure 3.5. Challenges in implementing

3.3.9. **Farmer evaluation of IS**

IS adopters were also asked about the prior usage of the land, environmental and economic impacts perceived after the adoption of IS, whether the farmer had plans to increase or decrease the area under integration, and whether he intended to implement consortium schemes (i.e. cultivation of maize and grasses in parallel, as second harvest) and/or forestry activities. Out of all IS adopters sampled, only two intended to decrease the area under IS, including an investment group that wanted to invest in a highly specialized system for cattle breeding and an individual farmer who decided to leave the agricultural sector for personal reasons. All others expressed satisfaction with the results generated by IS and wished to maintain the area that was being used for it, with a few adopters even intending to expand their IS area. IS adopters did recognize IS's environmental benefits, but just a few considered these as a motivation for adoption.

Concerning the introduction of forestry, farmers who did it were motivated by the profitability of the activity and/or because this was the most appropriate activity for a specific part of the property (usually where soils were sandy and crops would not grow so well). Those who did not intend to introduce forestry in their systems claimed that it did not make sense to do it from an economic point of view, and pointed at the difficulties in selling forest products. Almost none of the respondents mentioned "no possession of environmental license" as an impediment to adopt forestry, as depicted in Figure 3.6, confirming that access to credit (for which the license would be needed) was not a determinant factor for IS adoption.

IS adopters agreed that the rotation schemes led to production intensification, optimization of resource use, land value rising, provision of feed for cattle during the dry season and even a more pleasant natural environment. However, most of them did not intend to increase the share of their properties currently under IS and almost none saw IS as a business option that could replace their current systems (but, rather, as a complementary strategy).

Additional open ended-questions revealed that many producers were interested in IS when contributing to solve a specific problem in their properties. In Campo Novo do Parecis, for instance, traditional soya farmers decided to introduce cattle in their properties with the objective of disrupting pest cycles and solving other problems in the crop fields. In contrast, traditional cattle farmers from Tangará da Serra facing economic problems might have started cultivating crops as a way of increasing their total income and weather the crisis without leaving the market. In fact, substantial market power for beef slaughterhouses (Acrimat, 2012) may be a driver of IS adoption in some regions.

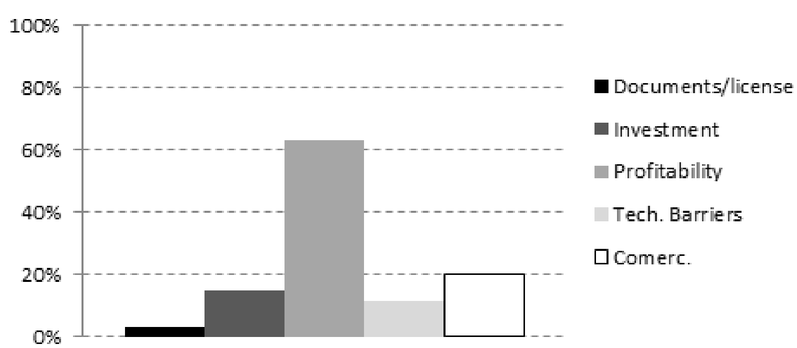

Figure 3.6. Obstacles to implement forestry activities

3.3.10. Exposure to information and connectedness

Most IS adopters are members of professional associations, suggesting that exposure to the latest innovations and contact with peers who already implemented new practices definitely increase the chances of IS adoption. The fact that associations often promote technical meetings, training sessions and other opportunities for the provision of technical support added to that.

The number of farmers who regularly hired a private consultant for farming operations is higher among IS adopters. Municipal unions, *FAMATO*, *APROSOJA*, *ACRIMAT* and *Fundação Mato Grosso* were the most mentioned entities as those who farmers had most contact with, and from which they received the most relevant information. The public extension bureau, on the other hand, was criticized for being essentially absent, and many respondents mentioned that extension agents often visited farms with the purpose of checking for compliance with environmental laws or tax payments.

In every cluster of surveyed farmers, it is clear that affiliations to unions were more common than to cooperatives. The few cooperatives mentioned by respondents were Arefloresta (which covers most of the systems with forestry activities) and smaller ones created by farmers with the purpose of sharing storage facilities or having better access to banking services. The rate of affiliation to unions was significantly higher among IS adopters.

Access to information on weather conditions and the agricultural market were generally higher among IS adopters. The difference between them and soya producers is not that significant, but is much bigger when compared with livestock producers – reflecting the typical profiles of the two enterprises. It is important to clarify that a few soya producers who claimed not to look for information on climate and market conditions themselves actually had access to that information through their private consultants. The fact that soya is much more sensitive to climate variations than cattle or trees, and that it is usually exported as a commodity (which implies almost no margin for price negotiations) explain why soya producers – both specialized and IS adopters – sought for information more frequently than farmers.

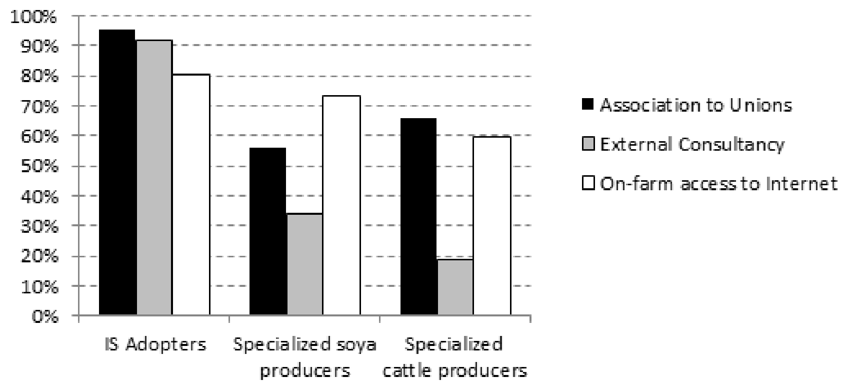

Figure 3.7. Exposure to information

3.3.11. **Financial aspects**

The level of indebtedness was highest among soy bean producers, followed by IS adopters and then livestock farmers. To a certain extent, this reflects their capitalization level and probably explains why adopters felt more secure to invest in the implementation of IS. All farmers including adopters and non-adopters seemed equally eligible to apply for loans from the bank (i.e. the average level of default on loans is practically the same among all interviewees) and credit availability was not an issue for neither IS adopters nor non-adopters – they all agreed that there was enough credit available. Nevertheless, external financing was much more common among IS adopters and specialized soya farmers than among specialized cattle producers, corroborating the assumption that the last had a relatively conservative investment profile and was highly risk-averse. Also, as depicted in Figure 3.8, cattle producers relied mainly on their own capital for farm-related expenses whereas IS adopters and specialized soya producers made use of credit on a regular basis:

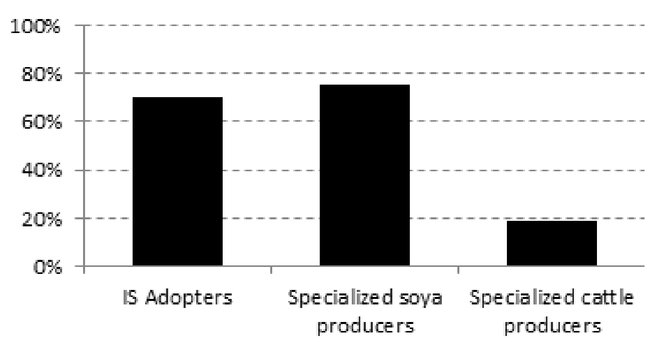

Figure 3.8. Regular usage of external financing among interviewees

The credit utilized by the first two groups comes from private and public financial institutions (particularly Banco do Brasil and Sistema de Crédito Cooperativo - Sicredi) and was used both for long-term investments and working capital. Finally, it is worth mentioning that the absolute amount of private credit used by soy bean producers – particularly from traders and retailers – was comparatively larger.

3.3.12. **The “ABC Credit Program”**

Survey results show that the ABC credit program was generally well-known by all clusters members (about 88% of the total) and many of the few farmers who had not yet heard of it were specialized cattle producers. The fact that most respondents got to know about it through bank agents, and that soya farmers are usually in close contact with banks, explain such difference. Results also show that many farmers would like to have ABC credit, but not necessarily with the intention to implement IS (most of them consider applying for it and using it for other expenses, since interest rates are so attracting).

The most striking finding of our study concerning credit is that the number of farmers who actually made use of the ABC credit program was very low among all survey participants. As depicted in Figure 3.9, only 17% of the respondents had applied for it and even fewer – 5.9% – succeeded in obtaining it. This is in accordance with the outcomes of our statistical analyses, which showed no association between having ABC credit and adopting IS (see Appendix 1).

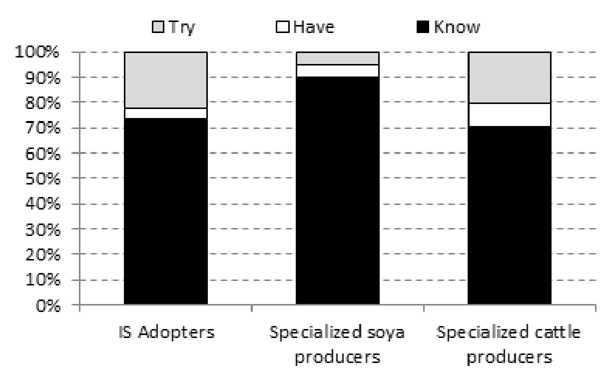

Figure 3.9. Respondents and the ABC Credit Program

Those farmers who had applied for the ABC credit lines mentioned bureaucracy as the main obstacle for the dissemination of the program. On the other hand, interest rates and grace period were positively evaluated, indicating that even though the credit line itself was appealing, farmers had been reluctant to take advantage of it due to excessive documentation requirements and prohibitively strict environmental laws.

Concerning the apparent irrelevance of credit provision through the ABC Credit Program for the adoption of IS, it is important to consider that credit might have a different effect for different groups of farmers. Thinking of standard technology diffusion curves as theorized by Rogers (2003), it is reasonable to expect that IS adopters who participated in this study were either pioneers or early adopters – and as such, would have been inclined to adopt the technology (irrespective of credit provision) due to their venturesome nature. On the contrary, farmers who did not yet adopt IS and were less open to innovations could be convinced to do it in the presence of credit. Although other innovations' diffusion curves may offer some hints on this issue, it would be difficult to predict how IS will diffuse exactly.

3.4. Discussion

Considering typical profiles of crop and livestock producers, experts and policymakers in Brazil expected the first to be more prone to the adoption of innovations. However, our empirical study refutes such expectation due to high soy bean prices on the one hand, and the possibility to improve degraded pasturelands by implementing rotation schemes on the other hand. Also, large commercial farmers are usually expected to present a higher rate of IS adoption; even though our study confirmed this assumption, it showed that such relationship was not exactly linear, and that the positive covariance between size and adoption holds true only up to a certain point (beyond which even larger farmers may have reasons to not adopt IS). In practice, this might happen when larger farmers – particularly crop producers – already reap substantial profits from their current activities and have little incentive to change their production systems.

The examples above clearly underline the importance of detailed research for reimplementation of federal development policies for agriculture. Particular characteristics of the technology under analysis and local conditions must be taken into account, as both have a major influence on the technology dissemination process.

Farm size and farmer resource endowments (particularly financial resources), cultural preferences, labor availability and know-how were the major factors driving the adoption of IS. Apart from certain particularities, IS adopters generally exhibited characteristics that qualified them as innovators; in addition to having a more favorable attitude towards change, they also seemed better able to cope with uncertainties and risks involved in the implementation of a new agricultural practice. In terms of communication behavior, they had more social participation than late adopters and were more highly interconnected through social networks (as confirmed by our study's results in terms of access and exposure to information).

After all, the potential of IS to expand in Mato Grosso is high, and farmers generally had a positive attitude towards it. They understood the advantages of specialized production (increased efficiency, specialized machines, economies of scale) as well as advantages of diversified production (reduced risk, optimization of resource use, etc.) and regarded IS as a compromise between these two models. In other words, they saw IS as a way to diversify what was until then a monoculture that might exhaust the soil, but without completely giving up the advantages of specialized production and economies of scale.

Producers' positive evaluation of IS was not explicitly based on carbon accumulation in the soil, but rather on the positive impacts of IS on productivity that result from carbon accumulation (that is, the changes perceived after the implementation of IS, as explained in section 3.3.6). The biophysical characteristics of the farms captured during the survey suggested an association between the presence of sandy soils and IS adoption; however, the risk-averse behavior of some IS adopters may have biased these results. As explained in section 3.3.2, some of them implemented IS in parts of their farms which were not the best for growing crops. In order to account for that and to check whether specific IS types/configurations are also associated to biophysical characteristics of the farms, it would be necessary to conduct a more detailed analysis (with measured data, at the plot level). The collection of reported data was based on the fact that, in practice, farmers may make imperfect decisions under imperfect information, which is crucial for the environmental impacts of agriculture (and environmental modeling and analysis are enhanced by this inference). As shown by our results, decision making under uncertainty is particularly relevant in the case of IS dissemination in Mato Grosso, given that IS were mostly recently implemented and IS adopters may be "early adopters" at this stage of the technological diffusion process (Rogers, 2003). Early adopters tend to be more venturesome by nature, and would often be willing to try out an innovative technology such as IS irrespective of information availability about soil and other biophysical factors.

Integrated Systems may assume different configurations, and these configurations may be equally diverse in terms of implementation and maintenance requirements, costs, yields, and management. Such differences are very important when assessing which factors determine the adoption of each IS type. Yet, it would be reasonable to expect that the curve of adoption follows the same dynamics as other technologies related to best management practices in agriculture, in the sense that it might take some time until adoption becomes widespread. In the meantime, farmers might get acquainted with IS; policies such as the ABC credit program can be improved; and successful pilot initiatives will prove the technology interesting from the technical and the economic perspectives. Policy-makers should not underestimate the influence of extraneous effects on farmer decisions to adopt IS (such as international market conditions and agricultural prices) nor neglect cultural elements that often hamper their ability to behave rationally.

As robust methods to calculate IS' profitability and optimal scale for each possible configuration are still to be created, especially because of long-term positive effects on productivity, it is still hard to determine farm size categories or thresholds under which IS are the best option from an exclusive economic point of view. Nevertheless, our results leave no doubts that IS constitute an interesting alternative for particular cases, including those where livestock farmers need to increase their profitability without giving up cattle ranching, or when specialized soya producers must combat pests and other problems that arise when monoculture is carried out for too many years. Future policies and incentives could increase the profitability of IS to a point where even the largest soya farmers would be interested in adopting it; however, under current market conditions (particularly high grain prices), this possibility does not seem realistic.

3.5. Conclusions

This paper looked into the current status of integrated systems adoption in Mato Grosso-Brazil and their dissemination potential among farmers in this region. As it investigated the determinants of IS adoption at one specific point in time, it could not capture long-term cumulative effects of different agricultural systems; nonetheless, it offers important elements for a deeper understanding of farmers' adoption behavior when public policies aimed at disseminating IS are being designed and implemented in Mato Grosso. In this sense, its empirical relevance relies not only on the importance of the region in terms of the world's agricultural production, but also on the fact that it meets a concrete demand for information imposed by the creation of the ABC Plan.

Even though the focus of the ABC Plan is the mitigation of climate change through the dissemination of low-carbon agricultural practices, it is important to bear in mind that IS have other important environmental advantages when compared to conventional monoculture systems (including soil and water conservation, animal well-being, biodiversity, among others).

The results presented here point at several venues for further research. The investigation of the dissemination potential of IS among smaller farmers is strongly recommended - particularly dairy farmers, whose production systems would directly benefit from such practices. The fact that IS are more widely spread among large farmers is positive considering that the main goal of the ABC Plan is the reduction of overall GHG emissions; after all, the share of small-scale holdings in Mato Grosso's overall GHG emissions is relatively small because they concentrate less land and usually employ less intense field operations than large farms. However, considering environmental and economic benefits potentially promoted by IS, it would be interesting to design small-scale business models that can be used on small-scale farms.

The impact that credit provision will have on IS adoption by different stakeholders is also something to be explored in the future, given that early and late adopters are likely to respond differently to such incentives. Likewise, the influence of biophysical conditions (such as soil types) on the adoption of specific IS configurations must be monitored in the longer run through data measured at the plot level, especially when the processes of technology adoption and diffusion reach stability and results are less prone to biases. The reassessment of IS adoption determinants in the longer run could serve as a starting point to answer whether results can be generalized to other regional contexts besides MT.

Finally, we recommend the exploration of whether alternative IS arrangements (such as shared tenancy or cooperation between specialized farmers) could help overcome the IS adoption constraints identified in the study (including limited investment capacity, labor availability or know-how necessary to introduce a new farming activity).

3.6. Acknowledgments

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3.8. Appendix 1 – Statistical tests

Survey variables:

- S1educ: Education Level (1 = Basic, 2 = High school, 3 = Graduate, 4 = Post-Graduate)
- s1origin: Origin (1 = South, 2 = South East, 3 = Centre-West)
- s1add_incsou: Additional income sources (0 = No, 1 = Yes)
- s1oth_farm: Ownership of other farm (0 = No, 1 = Yes)
- s1player: Owner Type (1 = Individual Producer. 2 = Investment Group)
- s2ownership: Do they rent from someone else? (0 = No, 1 = Yes)
- s2sand: Presence of sandy soils (0 = No, 1 = Yes)
- s2topog: Topography (1 = Flat, 4 = Hilly)
- s2mach_own: Machinery availability (1 = Idle units, 2 = Adequate, 3 = Lacking)
- s3tech_profile: Number of best agricultural practices performed on property
- s4CAR: Registered at CAR (0 = No, 2 = Yes)
- s9netw: Association to Cooperatives and Unions (0 = None, 2 = Cooperative OR Unions, 2 = Both)
- s9sector_info: Index of information access on agriculture, climate and market
- s9tech_assist: Index of access to assistance via: participation in trainings, visits from public extension services and private consultants
- s10ex_fin: Current reliance on external finance sources (0 = No, 1 = Yes)
- s10indebt: Farmers level of indebtedness (0 = None, 5 = Most)
- s11ABC_have: Use of ABC Credit (0 = No, 1 = Yes, 2 = Pending)
-

Procedure:

- For categorical variables, Risk ratio and Odds ratio were calculated to check for the chances of adoption given the exposure to a certain independent variable.
- For discrete variables, Chi-square tests and Fischer's exact tests were performed to check for association between them and the IS adoption.
- For continuous variables, Shapiro-Wilk W tests were performed to check for data normality; as there were not proven to be normally distributed, non-parametric tests were performed with them to check for possible association with IS adoption.

Summary of results:

Table A 3.1. Categorical variables with association – RR-Risk ratio/OR-Odds ratio (2x2).

Variable	RR*	OR*
S1add_incsou	3.267633	15.57764
s2sand	1.535613	2.377289
s10ex_fin	1.6125	2.324324

Table A 3.2. Discrete variables – Chi-square/Fischer's exact test.

Variable	Chi-square*	Pr	Fischer's exact test	Outcome
S1educ	31.6016	0.000	0.000	H0 rejected
S1origin	34.3545	0.000	0.000	H0 rejected
S1add_incsou	41.3881	0.000	0.000	H0 rejected
S1oth_farm	68.3582	0.000	0.000	H0 rejected
S1player	0.0639	0.800	1.000	No assoc.
S2ownership	0.7587	0.384	0.498	No assoc.
s2sand	4.8235	0.028	0.033	H0 rejected
s2topog	4.1903	0.123	0.119	No assoc.
s2mach_own	23.2957	0.000	0.000	H0 rejected
s3tech_profile	36.733	0.000	0.000	H0 rejected
S4CAR	0.398	0.528	0.562	No assoc.
S9netw	23.5375	0.000	0.000	H0 rejected
S9sector_info	12.317	0.006	0.002	H0 rejected
S9tech_assist	52.1775	0.000	0.000	H0 rejected
S10ex_fin	5.4188	0.020	0.022	H0 rejected
S10indebt	37.1325	0.000	0.000	H0 rejected
S11ABC_have	1.2877	0.525	0.711	No assoc.

Table A 3.3. Continuous variables – Shapiro-Wilk W test for normal data.

Variable	Obs	W	V	z	Prob > z
s1age	134	0.95010	5.273	3.747	0.00009
s2area_tot	134	0.85414	15.413	6.164	0.00000
s2staff	134	0.77935	23.316	7.097	0.00000
s2dist_road	134	0.87520	13.187	5.813	0.00000

Table A 3.4. Continuous variables – Non parametric tests.

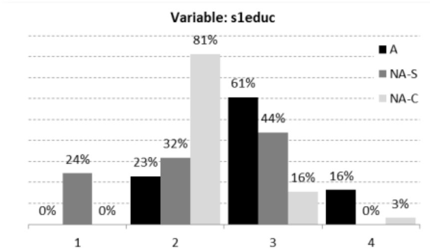
Variable	z	prob > z
S1age	-0.809	0.418
S2area_tot	-4.317	0.000
S2staff	-5.524	0.000
s2dist_road	5.545	0.000

3.9. Appendix 2 – Graphs of survey outcomes (Figure A 3.1)

Survey variables:
See Appendix 1 (variable coding is the same for graphs and statistical analyses).

Groups depicted in the graphs:

- *A*: Integrated Systems Adopters
- *NA-S*: Non-Adopters, specialized in soybean production
- *NA-C*: Non-Adopters, specialized cattle produces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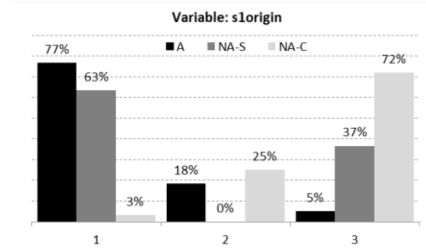
A
NA-S
NA-C
0% 24% 0%
23% 32% 81%
61% 44% 16%
16% 0% 3%
1 2 3 4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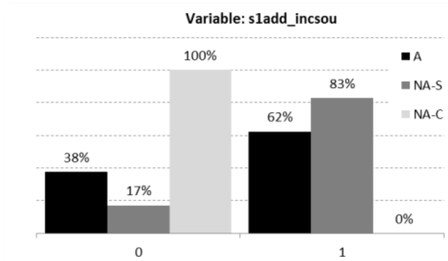
NA-S
NA-C
77% 63% 3%
18% 0% 25%
5% 37% 72%
1 2 3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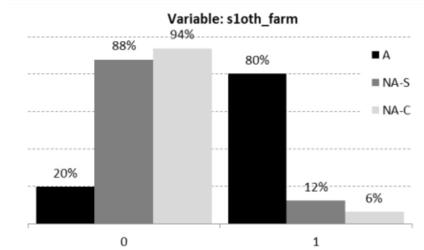
A
NA-S
NA-C
38% 17% 100%
62% 83% 0%
0 1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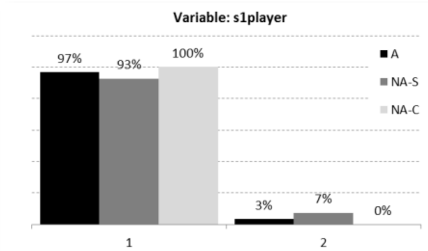
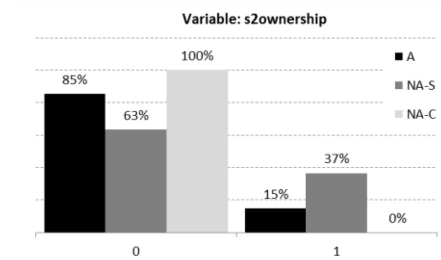
A
NA-S
NA-C
20% 88% 94%
80% 12% 6%
0 1


Variable: s1player
A
NA-S
NA-C
97% 93% 100%
3% 7% 0%
1 2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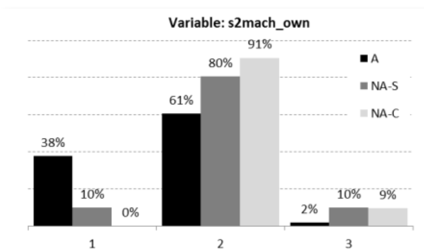
A
NA-S
NA-C
85% 63% 100%
15% 37% 0%
0 1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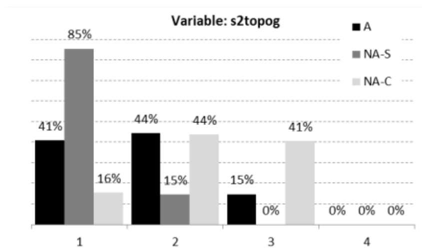
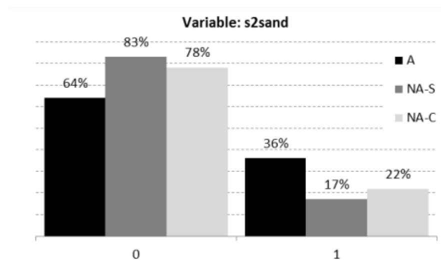
A
NA-S
NA-C
38% 10% 0%
61% 80% 91%
2% 10% 9%
1 2 3


Variable: s2topog
A
NA-S
NA-C
41% 85% 16%
44% 15% 44%
15% 0% 41%
0% 0% 0%
1 2 3 4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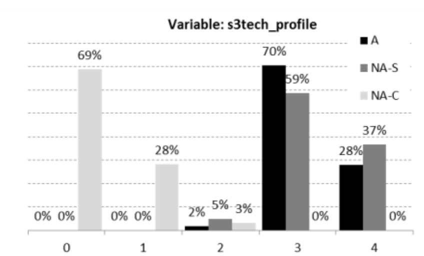
A
NA-S
NA-C
64% 83% 78%
36% 17% 22%
0 1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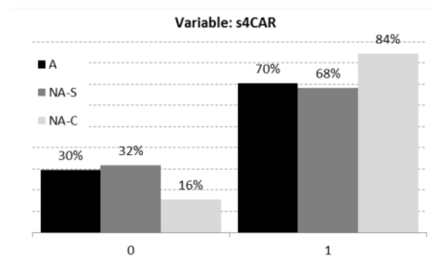
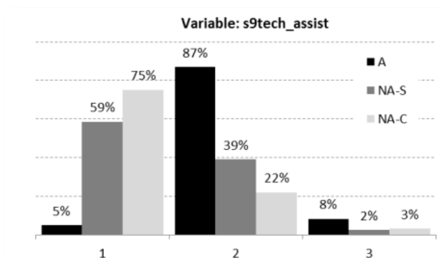
A
NA-S
NA-C
0% 0% 69%
0% 0% 28%
2% 5% 3%
70% 59% 0%
28% 37% 0%
0 1 2 3 4


Variable: s4CAR
A
NA-S
NA-C
30% 32% 16%
70% 68% 84%
0 1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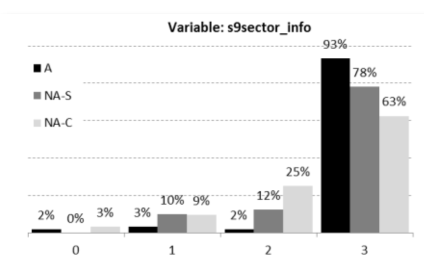
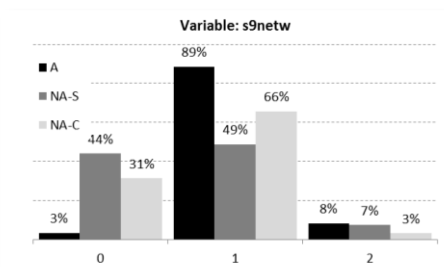
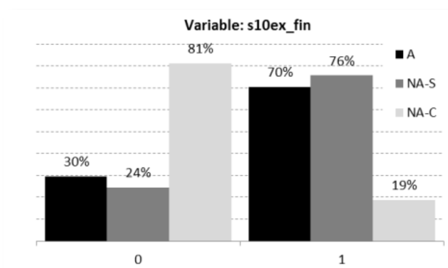
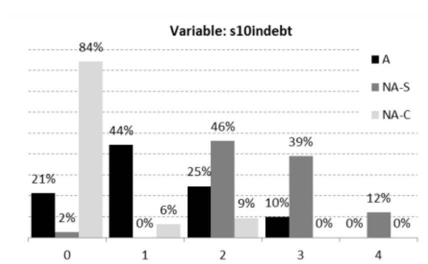
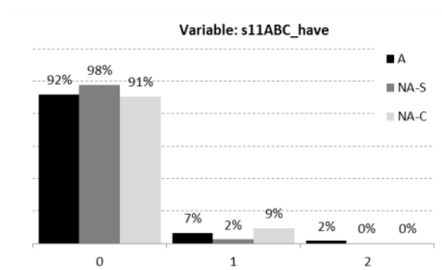
A
NA-S
NA-C
5% 59% 75%
87% 39% 22%
8% 2% 3%
1 2 3


Variable: s9sector_info
A
NA-S
NA-C
2% 0% 3%
3% 10% 9%
2% 12% 25%
93% 78% 63%
0 1 2 3


Variable: s9netw
A
NA-S
NA-C
3% 44% 31%
89% 49% 66%
8% 7% 3%
0 1 2


Variable: s10ex_fin
A
NA-S
NA-C
30% 24% 81%
70% 76% 19%
0 1


Variable: s10indebt
A
NA-S
NA-C
21% 2% 84%
44% 0% 6%
25% 46% 9%
10% 39% 0%
0% 12% 0%
0 1 2 3 4


Variable: s11ABC_have
A
NA-S
NA-C
92% 98% 91%
7% 2% 9%
2% 0% 0%
0 1 2

4. The wide-scale adoption of integrated crop-livestock systems in Mato Grosso, Brazil: Evidence from the household and regional levels

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Abstract

Integrated crop-livestock systems (iCL) are advocated as a promising strategy to intensify agricultural production and rehabilitate degraded pastures while mitigating GHG emissions. Although the number of iCL in Brazil has increased over the past few years, iCL still occupies a small share of the country's total agricultural area. We investigate the factors that may influence the wide-scale dissemination of iCL in the state of Mato Grosso, a globally important center of agricultural production. This includes, on the one hand, the characteristics of individual farmers and, on the other, the biophysical, socioeconomic, and institutional characteristics of each county. We find that the occurrence of iCL is associated with higher levels of knowledge and proximity to specific supply chain infrastructure elements for crop and livestock production. On average, iCL adopters are more educated and enjoy better access to technical assistance and sector information than specialized farmers or ranchers. Most iCLs are concentrated near established soy areas and greater similarity exists between counties with iCL and soy-dominant counties vs. pasture-dominant counties. Finally, the presence of soy and pasture in a region does not predict iCL occurrence, revealing that the dissemination of iCL involves unique drivers and constraints.

4.1. Introduction

Since 2004, when the deforestation rate in Brazil reached its peak, agricultural production in the Brazilian Amazon has appeared increasingly decoupled from forest clearance. Indirect impacts of this expansion in other biomes are still uncertain and a minor part of the overall decline in deforestation is attributable to periods of lower soy profitability and other circumstantial factors. Nevertheless, specialists agree that improved anti-deforestation policies and voluntary programs contributed to the conservation of forest despite the growing agricultural output achieved in the same period (Nepstad, 2009; Soares-Filho et al., 2010; Assunção et al., 2012; Macedo, 2012; DeFries et al., 2013, Gibbs et al., 2015).

Whether this positive trend will hold in the long run is yet to be seen. A slight increase in deforestation rates was observed from 2012 to 2013 (INPE 2015), probably caused by land speculation and specific infrastructure works (IPAM, 2014). Deforestation on small-scale properties persists (Godar et al., 2014) and sharper oscillations in the prices of agricultural commodities may lead to the expansion of cropland and displacement of cattle into the forest as has occurred in the past (Barona et al., 2010; Nepstad et al., 2014).

In an effort to prevent further forest clearance and associated greenhouse gases (GHG) emissions, the Brazilian Federal Government has been investing in technologies that increase the productivity of existing crop and livestock production systems and restore degraded lands (Government of Brazil, 2014). Particular attention is directed at cattle since roughly 20% of Brazil's total land area is devoted to pasture that, on average, supports less than one animal per hectare (IBGE, 2006). The Government's rationale is in line with several recent studies that already highlighted the large opportunities for productivity improvement in the Brazilian cattle sector (Cohn et al., 2014; Strassburg et al., 2014). Although improved productivity cannot guarantee land sparing (Angelson & Kaimowitz, 2008) and often enhances the attractiveness of a particular area for agricultural production, it is a necessary complement to more direct conservation policies for the continued increase of agricultural output at the national scale (Godfray at al., 2010; Tilman et al., 2012).

One promising technology for improving the productivity of livestock production in Brazil is the use of Integrated Systems (IS). By combining crops, livestock and/or forestry in the same area, IS have the potential to generate higher output values through positive interactions amongst their components. The synergies between crop, livestock and forestry – including the degree of complementarity between the systems' components and the potential to optimize resource use – vary according to the exact IS configuration and species involved. Integrated crop-livestock systems (iCL), a specific type of IS that consists of the rotation of farming and ranching on the same land area, have been shown to improve the productivity of crops and livestock by enhancing overall soil fertility through improved nutrient cycling (Salton et al., 2013; Carvalho et al., 2014; Lemaire et al., 2014). Integrated crop-livestock systems also offer increased resilience against economic and biophysical stresses versus specialized crop or livestock operations (FAO, 2007; Thornton & Herrero, 2015). Some forms of iCL, such as integrated beef-maize production, involve high levels of synthetic inputs and low species and habitat diversity as compared to some other mixed systems (Bungenstab, 2012). However, their lower level of complexity may increase their acceptance in places where large-scale specialized agriculture prevails (Gil et al., 2015).

Integrated systems in general and iCL in particular are very promising in the state of Mato Grosso, which spans the two largest Brazilian biomes (the Cerrado savannah and the Amazon rainforest). In the last two decades, agricultural expansion and deforestation in Mato Grosso occurred on a larger scale than in any other region in Brazil. Crop farming expanded from 2.4 million hectares in 1990 to 11 million hectares in 2012 (Richards et al., 2012; Gasparri et al., 2013), while direct conversion of forest to cropland and the conversion of forest to pasture followed by pasture displacement by cropland were common (Barona et al., 2010, Morton et al., 2006). Nowadays, besides having the largest soybean area in the country (8.6 million hectares in 2013/14) (CONAB, 2014), Mato Grosso also has the largest herd (28 million animals) and pasture area (26 million hectares) (IMEA, 2010). Such figures contrast with cattle stocking rates as low as 0.5 animal/hectare found in some regions and the more than 2 million hectares of degraded pasture (IMEA, 2010) – both major sources of direct and indirect GHG emissions (Galford et al., 2010). A recent study estimates that the adoption of iCL could more than double the stocking rates of degraded pastures (Observatorio ABC, 2014a) and improve soil quality where organic matter has been lost after years of monoculture (Peron & Evangelista, 2004; Oliveira et al., 2013).

Due to the relatively high profitability of crops in Mato Grosso (Mann et al., 2014), the state has already started experiencing a shift from monoculture soy production to double cropping soy and maize (VanWey et al., 2013; Spera et al., 2014) and the conversion of pasture into cropland (Cohn et al., *in review*). In order to boost wide-scale adoption of IS as a third, more sustainable intensification pathway, Brazilian authorities approved the National Policy of Integrated Crop-Livestock-Forestry Systems (Government of Brazil, 2013) and created a new EMBRAPA[6] unit exclusively dedicated to the research and development of integrated systems. In addition, the Ministry of Agriculture launched the Low-Carbon Agricultural Plan (or simply "ABC Plan") in 2010 to facilitate capacity building, improve technical assistance and offer special credit lines to farmers adopting any kind of IS or any of other selected low-carbon agricultural practices – namely no-tillage farming, nitrogen biological fixation, restoration of degraded pastures, commercial forest plantations and treatment of animal residues (Government of Brazil, 2011). The Plan is part of the country's National Policy for Climate Change, which defines a voluntary target for GHG emissions reduction of 36.1% - 38.9% by 2020 (Government of Brazil, 2009). The targets of the ABC Plan include an increase in IS by 4 million hectares, which would avoid the emission of about 18-22 million tons of Carbon dioxide equivalent (CNA 2012).

According to official estimates based on PROBIO[7] data, the potential area for IS expansion in the entire country is greater than 67 million hectares, but until 2010 IS still occupied only 1.5 million hectares (Balbino et al. 2011). The dissemination of IS across Mato Grosso has been particularly slow, reaching only 90,000 (0.4%) of the 25 million hectares of agriculture in that state (Balbino et al. 2011). It is estimated that roughly 89% of this total IS area were devoted to iCLs (Gil et al., 2015). Concerning credit, less than 5% of all ABC loans issued since 2011/12 have been allocated to IS (Observatorio ABC, 2013) and a large part of those was concentrated in Southern Brazil (Observatorio ABC, 2014b).

Understanding the drivers and constraints of iCL adoption is essential for the successful implementation of climate-related policies put forward by the Brazilian Government and for the assessment of the broader impacts of iCL (non-) adoption on land use change and food production. Yet, to the best of our knowledge, no study has ever tried to capture the aggregate effect of biophysical, socioeconomic, and institutional requirements for iCL adoption on the spatial variation of iCL dissemination. Existing case studies of individual farms or experiments offer important insights into the economic and environmental benefits of IS under

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[6] EMBRAPA (in Portuguese, "Empresa Brasileira de Pesquisa Agropecuária") is the Brazilian National Agricultural Research Institute.

[7] PROBIO (in Portuguese, "Projeto de Conservação e Utilização Sustentável da Diversidade Biológica Brasileira") is a project for the conservation and sustainable use of the Brazilian biological diversity for which land cover maps of all Brazilian biomes were generated. It is conducted by the Brazilian Ministry of Environment and co-funded by the Brazilian Federal Government, the Global Environmental Facility (GEF), and the World Bank.

specific conditions, but do not elucidate the barriers to scaling up production nor can be generalized to understand regional- or state-level conditions.

In this paper we examine the main spatial factors associated with the occurrence of iCL in Mato Grosso, Brazil. We argue that iCL systems have unique characteristics that distinguish them from specialized agricultural systems, and propose an analytical framework based on specific adoption determinants that arise from these characteristics. We test the extent to which variables observable at the household and county levels are associated with iCL adoption and then compare the findings from both scales. We finally discuss these finding in light of past research regarding agricultural behavior and land use, and identify potential leverage points for boosting iCL dissemination from a public policy perspective.

4.2. Background and analytical framework

The economic geography and land use science literature has identified numerous factors that influence agricultural land use choices. These include macroeconomic conditions directly influencing the relative prices of different products (e.g. oscillations in demand and input prices) (Richards et al., 2012; Garrett et al., 2013a); national factors associated with agricultural, environmental, and fiscal policy (e.g. subsides, conservation reserve requirements, credit for different cropping systems) (Schnepf et al., 2001, Garrett et al., 2013b); biophysical conditions (e.g. soil quality, slope, precipitation patterns) (Vera-Diaz et al., 2008; Mann et al., 2010; Spera et al., 2014); transportation costs (e.g. distance to markets and road quality) (Walker et al., 2009); as well as household socioeconomic indicators (e.g. land tenure, access to capital, age, education, experience, farm size) (Lee, 2005; Knowler & Bradshaw, 2007). However, very few studies have tried to explain land management choices in Brazil that involve the adoption of different intensification strategies and diverse production systems in particular.

The decision of whether to manage the land via integrated or segregated production units involves utility tradeoffs. These may include, among others, complexity versus simplicity, labor versus leisure, high risk versus low risk, and long term resilience versus short term profit maximization (Garrett et al., 2015). Factors which are particularly important for IS adoption thus comprise labor availability, access to markets, information and technology, tenure security, the level of risk associated with each management system, and farmers' individual preferences concerning risk, leisure, and complexity. The extent to which such factors influence IS adoption also depends on the specific type of IS and the agricultural context under analysis. For instance, one study in the US corn-belt concluded that the four major factors influencing the adoption of iCL in this region were i) the tradition and norm of single crop production, ii) the ease of management in specialized systems, iii) the lower managerial intensity of specialized systems, and iv) the lack of appreciation for farm level performance versus singe crop yields (Sulc & Tracy, 2007).

The enabling conditions for iCL adoption are not always observable at a single level of analysis, ranging from household level incentives, individual preferences and capacity to larger scale infrastructural and biophysical constraints. In Mato Grosso, specialized farmers and specialized ranchers have shown different perceptions and attitudes towards IS, reflecting how the two groups differ in terms of demographic characteristics, risk aversion, and investment profile (Gil et al., 2015). The level of local supply chain infrastructure (e.g. transportation networks, storage facilities and input retailers) is also a crucial limitation of agricultural development in Brazil (Bowman et al., 2012; Garrett et al., 2013a, VanWey et al., 2013) and may co-determine the economic feasibility of crop-livestock integration. The pool of knowledge capital in a given region – largely reflected by the presence of agricultural research and extension agencies – plays an important role in land use decisions (Caviglia & Kahn, 2001; Pretty & Uphoff, 2002, Wollni & Brümmer, 2012) and should be examined carefully since IS are complex and often require skilled labor. Because iCL is still a novel technology in Mato Grosso, access to information and technical assistance via formal channels (e.g. state research agencies), social networks (e.g. neighbors and cooperatives), or local agribusinesses is relevant not only because it may facilitate access to information, but because it enables exposure to the technology itself (Jepson, 2006). Finally, the costs of transitioning from a segregated to an integrated production system – particularly the incorporation of crop farming by specialized ranchers – may be high for soil preparation and machinery acquisition (Balbino et al., 2011). This often makes the availability of initial capital an important iCL adoption requirement.

The unique characteristics of iCL as compared to specialized agricultural systems in Mato Grosso were extracted from the existing literature on integrated systems (Bonaudo et al., 2014; Lemaire et al., 2014; Alves et al., 2015; Thornton & Herrero, 2015) and are summarized in Figure 4.1. Next to these characteristics are specific adoption determinants that arise from them. Together, unique characteristics and adoption determinants constitute the analytical framework used in this paper to inform the selection of variables tested throughout the analysis.

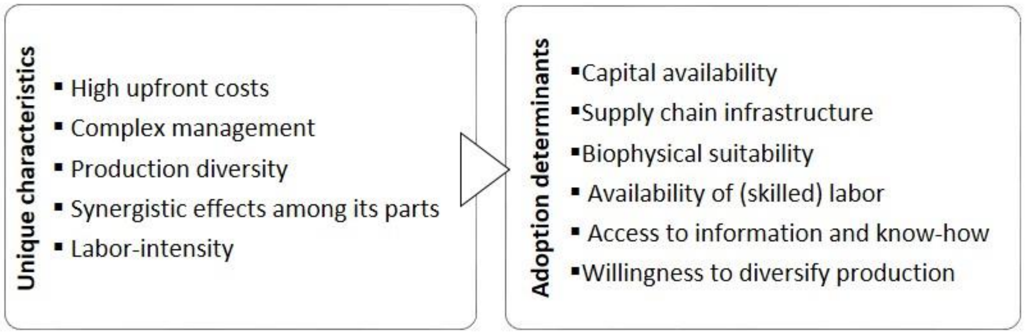

Figure 4.1. Unique characteristics of existing iCL as compared to specialized agricultural systems in MT and the adoption determinants that arise from those characteristics.

According to the proposed framework, almost all requirements outlined in the right box of Figure 4.1 are relevant at both the household and county levels. *Capital availability* determines household's ability to undertake high upfront costs for possibly longer-term payouts and is a function of income level and access to credit. From an aggregate perspective, capital availability depends on the aggregate economic activity in each county and overall credit allocations to that region from the government. Related to capital availability are the *costs* associated with iCL adoption versus non-adoption; the first refers to conversion costs, which are a function of farm size and current management practices, while the second refers to opportunity costs faced by each household. *Biophysical suitability* refers to favorable agro-climatic conditions for farming and/or ranching, which at the household level include the soil type and slope and at the regional level include average precipitation and temperature conditions. *Availability of skilled labor* depends on household demographics, but also county-level labor markets. *Access to information and know-how* are a function of the farmer's own education level but also whether he or she obtains technical support through social networks, private consultants or trainings and whether extension agents and other organizations are present at the county level. The existence of s*upply chain infrastructure* is represented by the presence of marketing, transportation, and processing services for all products in the iCL system and households' access to these services. The only variable uniquely relevant at the household level is *willingness to diversify production*, related to individual preferences regarding complexity, leisure and time, here hypothesized as correlated to cultural and geographic background (Daugstad et al., 2006; Nielsen & Reenberg, 2010).

4.3. Material and methods

We examine the relationship between the adoption requirements proposed above and current levels of iCL adoption at the household and county scales1using a combination of regression analysis and analysis of variance methods. The first part of the study, aimed at revealing which factors were associated with iCL adoption, comprised regression analyses based on the following model:

$$iCL\ adoption = f(K, C, S, B, L, I)$$

Where iCL adoption is a function of six adoption requirements: capital availability (K), costs (C), supply chain infrastructure (S), biophysical suitability (B), labor availability (L), as well as information access (I).

The specific variables used to represent each of the terms of the above equation are listed in Table 4.1 and Table 4.2 along with their descriptive statistics and, in the case of secondary data, respective sources. The inclusion of these variables in the model follows the rationale outlined in Figure 4.1, but some variables warrant additional explanation. “Maize area” is a proxy for double cropping, one of the most profitable land uses in Mato Grosso over the last years (VanWey et al., 2013). Double cropping could be either a complement or substitute to iCL, depending on the type of iCL in question. “Region of origin” refers to the region where the producer was born and controls for unobserved cultural factors that are likely to influence land use decisions. “Amaggi Group” controls for the presence of a large, vertically integrated Brazilian soy trader that is also a major land owner in Mato Grosso. Amaggi’s production decisions are often unique given its strong trade linkages with Europe and growing brand identity as an environmentally responsible soy producer (often non-GM and RTRS certified) (Garrett, 2013c). Theoretically this niche position could increase their incentive to adopt iCL. The rest of the variables are self-explanatory.

For the household analysis, we applied a logistic regression since the dependent variable was the adoption or non-adoption of iCL by each household. We used primary data collected by the first author in 2012/13 (Gil et al. 2015) from 145 respondents, of which 54 were iCL adopters, 59 were specialized soy farmers, and 32 were specialized cattle ranchers.[8] For the

[8] While the original study by Gil et al. (2015) sampled farms with any type of IS, we utilize only the data from farms with iCL systems, which comprised 89% of the original sample. Those with forestry were excluded from this analysis because their adoption requirements are quite different. Households with forestry comprised only 11% of the total IS adopters in the original sample.

county analysis we applied an OLS regression given that the dependent variable was the total number of iCL properties in each county. We used secondary data and mapped counties with iCL according to the findings of Gil et al. (2015) and data on ABC credit issuance from two Brazilian banks – Banco do Brasil and BNDES (Observatorio ABC, 2014b).

We did not identify multicollinearity between the variables included in the regressions (see Appendix 1), but we did identify spatial autocorrelation in the county-level regression through the Moran's I test. In order to control for spatial autocorrelation effects, we ran the original OLS regression for a second time incorporating additional spatial control variables based on a Euclidean distance-matrix (see Appendix 2 for details on the spatial analysis).

Table 4.1. Description of the variables used in the household-level analysis, collected during field research by the first author in 2012/13.

Household-level variables	Description	Mean	Std. Dev.	Min	Max
Capital availability					
Farm ownership status	Binary: Whether the farmer owns the land he works with (No, Yes)	no (19%), yes (81%)			
External financing sources	Binary: Whether the household relies on any external financing source (No, Yes)	no (34%), yes (66%)			
Level of indebtedness	Continuous: Score - 1 (min.) to 5 (max.)	0 (27%), 1 (18%), 2 (28%), 3 (20%), 4 (5%)			
Costs (adoption/non-adoption)					
Total farm size	Continuous (in hectares)	4038.7	2287.2	300	27800
Double cropping	Continuous (in hectares of maize)	861.3	874.7	0	1
Distance to the nearest road	Continuous (in kilometers)	10.6	17.5	0	75
Biophysical suitability					
Farm topography - flat	Continous: Score - 1 (min.) to 4 (max.)	0.32	0.47	0	1
Presence of sandy soils	Binary: Whether there are sandy soils in the property, according to landowners (No, Yes)	no (74%), yes (26%)			
Labor availability					
Number of farm workers	Countinuous (in number of employees)	3.3	1.2	3	80
Information & know-how					
Education level	Categorical: Basic (a), High School (b), Graduate (c), Post-graduate (d)	a (9%), b (41%), c (42%), d (7%)			
Access to sector information	Categorical: Index for access to information on agriculture, climate and/or market (1,2,3)	1 (7%), 2 (11%), 3 (82%)			
Access to technical assistance	Categorical: Index for participation in trainings, visits of extension services and/or private consultants (1,2,3)	1 (44%), 2 (52%), 3 (4%)			
Participation in networks	Binary: Whether producers are members of professional associations and/or unions or not	no (23%), yes (77%)			
Region of origin - South	Binary: Whether the household comes from Southern Brazil (No, Yes)	no (85%), yes (15%)			

Table 4.2. Description of the variables used in the county-level analysis and their respective sources.

Variable	Description	Source	Mean	Std.Dev.	Min	Max
Capital availability						
Per Capita GDP	Per capita GDP (in BRL/year) in 2014	IBGE	19044	13181	6607.86	80407.08
Presence of credit union offices	Presence of credit unions (SICREDI) in 2013 (binary)	SICREDI		no (25%), yes (75%)		
Access to ABC loans	Total amount of ABC loans issued in a given county since the beginning of the ABC credit program in 2011/12 divided by the number of properties of that county (in BRL/farm)	Observatório ABC, FGV	236	1003	0	7804.664
Costs (adoption/non-adoption)						
Average farm size	Weighted average size farms for 5 size categories: <500ha, 500-1000ha, 1000-2500ha, 2500-5000ha, >5000ha	INCRA	639	423	265.9574	2450.521
Average land price	Average price of cropland in 2013 (in BRL)	FNP Economics	10965	4655	6000	20000
Average soy productivity	Average productivity of soy (kg/ha) in 2013	IBGE	2324	1278	0	4500
Supply chain infrastructure						
Cooperative membership levels	Percentage of temporary crop establishments selling through cooperative in 2006	IBGE	2.2	7.2	0	43
Presence of Amaggi Group	Presence of farms owned by the Amaggi Group in 2013 (binary)	Amaggi Group		no (97%), yes (3%)		
Number of slaughtershouses	Number of slaughterhouses in 2012	MAPA	0.3	0.6	0	4
Soy area in 2006	Area dedicated to soy farming in 2006 (in hectares)	IBGE	41297	85601	0	597858
Biophysical suitability						
Precipitation	Average monthly rainfall – March-May	IRI/LDEO Climate Data Library, 2014	14	5	973.1554	1673.755
Temperature	Average daily temperature – March -May	Willmott & Matsuura, 2001	24	1	22.775	27.525
Information & know-how						
Presence of Embrapa experiments	Presence of farms where Embrapa conducts IS experiments in 2014 (binary)	Embrapa		no (93%), yes (6%)		
Technical assistance	Percentage of farmers who received technical assistance from the government, NGOs, cooperatives and/or associations	IBGE	197	144	15	675

The second part of the study was aimed at contrasting crop, livestock and iCL adoption/occurrence with respect to the variables identified as significant in the regressions. Households were sorted according to their primary activity (soy farming or cattle ranching) and whether they had adopted iCL. Analogously, counties were categorized according to their predominance of soy farming or pasture and whether they had iCL. Soy and pasture predominance at the county level was calculated through a percentile-based method (see Appendix 3). In order to prevent counties with very small soy or pasture areas from biasing our results, we only considered those above a pre-defined cut-off point, i.e. the 30th percentile in terms of share of arable land dedicated to soy and pasture within each county. This corresponds to less than 0.19% of their arable land allocated to soy and less than 20% of their arable land allocated to pasture. The resulting categories were then arranged into three mutually exclusive major groups: "iCL" (counties with iCL); "Pa" (counties with pasture and no iCL); and "So" (counties with soy and no iCL or pasture). Altogether, these three categories totaled 132 of the 141 counties of Mato Grosso (see Table 4.3). Soy appeared as a major land use in all counties with iCL, except for 5 counties which had iCL and pasture only. The results obtained for households and counties were finally compared through a multivariate analysis of variance (MANOVA) and Tukey's post-hoc tests.

Table 4.3. Code, description, number of observations, corresponding percentage and cumulative percentage of three new county groups.

Group code	Group description	Frequency	Percentage (%)	Cumulative percentage (%)
"iCL"	All counties with iCL	41	31.06	31.06
"Pa"	Counties with pasture and no iCL	78	59.09	90.15
"So"	Counties with soy only	13	9.85	100
	Total	132	100	

4.4. Results

4.4.1. Household level

The results of the household logistic regression model indicate that producers with higher capital availability and access to information were more likely to adopt iCL, while producers from the South and/or with more debt were less likely to do so (see Table 4.4). Variables related to biophysical conditions and access to skilled labor were not significant in the model. Average education level and access to technical assistance were significantly higher among iCL adopters than among ranchers and farmers (see Table 4.5, Figure 4.2). Level of indebtedness was highly variable both within and across all three groups.

*Table 4.4. Results of the logistic regression on iCL adoption at the household level (N=145). ** P<0.01, *P<0.05. (R2 = 0.75).*

Household-level variables	Odds ratio coefficients	Std.Err.
Farm ownership status	14.94	22.56
External financing sources	1.56	1.53
Level of indebtedness	0.22**	0.13
Total farm size	1.00	0.00
Double cropping	3.85	4.15
Distance to the nearest road	0.97	0.02
Farm topography - flat	6.30	11.71
Presence of sandy soils	5.37	6.86
Number of farm workers	1.10	0.07
Education level	5.22**	3.31
Access to sector information	4.43*	3.03
Access to technical assistance	34.04**	33.43
Participation in networks	10.26	13.83
Region of origin - South	0.01**	0.01

*Table 4.5. One-way analysis of variance of the five variables identified as significant in the household model. Household groups "iCL", "Famers" and "Ranchers" refer, respectively, to iCL adopters, specialized farmers and specialized ranchers. **P<0.01, *P<0.05*

Household variable	Groups	Constrast	Std.Err.
Region of origin	Farmers vs iCL	0.38	0.14
	Ranchers vs iCL	1.37**	0.16
	Ranchers vs Farmers	0.99**	0.16
Education level	Farmers vs iCL	-0.69**	0.13
	Ranchers vs iCL	-0.67**	0.15
	Ranchers vs Farmers	0.01	0.15
Access to technical assistance	Farmers vs iCL	-0.67**	0.09
	Ranchers vs iCL	-0.76**	0.10
	Ranchers vs Farmers	-0.09	0.10
Access to sector information	Farmers vs iCL	-0.12	0.12
	Ranchers vs iCL	-0.37*	0.14
	Ranchers vs Farmers	-0.25	0.14
Level of indebtedness	Farmers vs iCL	1.21**	0.16
	Ranchers vs iCL	-1.05**	0.19
	Ranchers vs Farmers	-2.26**	0.19

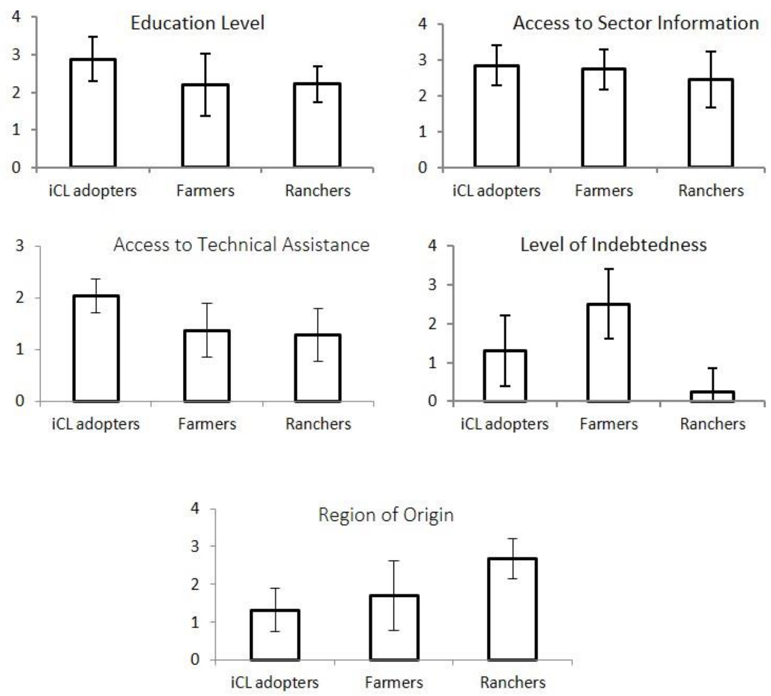

Figure 4.2. Contrast between iCL adopters, specialized farmers and specialized ranchers with respect to the five variables identified as significant in the household model. Bars indicate means and whiskers indicate variance.

4.4.2. **County level**

Existing iCL systems are highly clustered (see Table A 4.4 for Moran's I results) and their presence is common in regions with dense cropland areas (see Figure 4.3A). The spatial distribution of iCL across Mato Grosso is influenced by the interplay with other variables as well, being higher in counties (or near counties) with Embrapa experiments and slaughterhouses, and lower in regions where the Amaggi Group has a strong presence (see Figure 4.3B, Table 4.6).

The results of the county OLS regression model indicate that access to information and attributes of the supply chain were significant determinants of iCL adoption (Table 4.6). In particular, farms located in or near counties with Embrapa experiments and state inspected slaughterhouse that have had higher past levels of soybean production were all more likely to adopt iCL (see Table 4.6). However, farms located in regions where the Amaggi Group has a strong presence were less likely to adopt iCL. Biophysical conditions and costs (including credit availability) were not significantly associated with iCL levels, aside from *per capita* GDP – which was only significant in the model without spatial control variables.

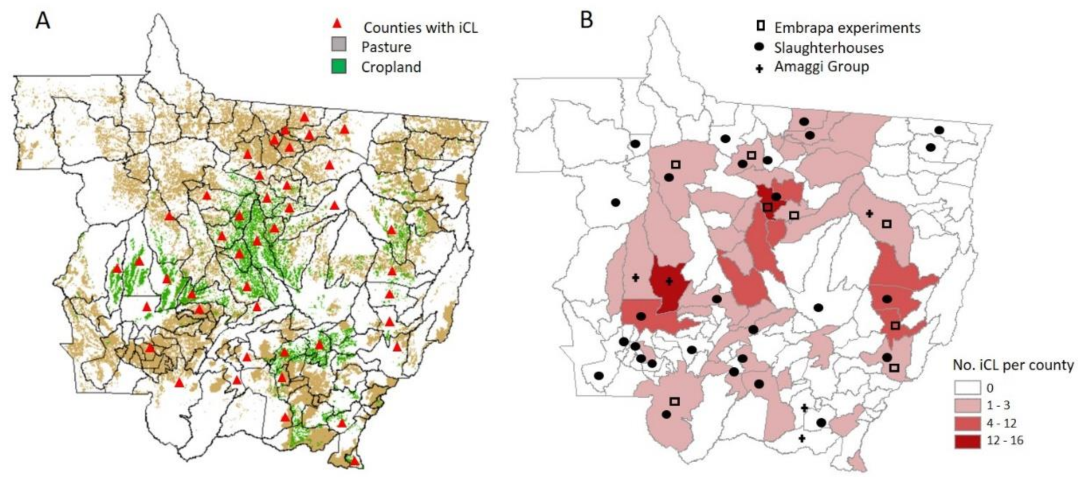

Figure 4.3. (A) Map of cropland, pasture and iCL in Mato Grosso's municipalities in 2014/15. (B) Map of iCL, Embrapa experiments, slaughterhouses and the Amaggi Group in Mato Grosso in 2013.

*Table 4.6. Standardized coefficients obtained from OLS regression on the adoption of iCL at the county level without spatial correlation effects (R2 = 0. 4132) and with spatial correlation effects (R2= 0.4982). **P<0.01, *P<0.05.*

County-level variables	No spat. autocorr.		With spat. autocorr.	
	Coef.	Std.Err.	Coef.	Std.Err.
Per Capita GDP	-0.23**	0.10	-0.45	0.35
Presence of credit union offices	0.01	0.16	0.02	0.17
Access to ABC loans	-0.07	0.07	-0.11	0.07
Average farm size	0.10	0.09	0.03	0.11
Average land price	0.09	0.09	0.08	0.18
Average soy productivity	0.01	0.08	0.00	0.24
Cooperative membership levels	-0.18	0.11	0.31	0.19
Presence of Amaggi Group	-0.54	0.30	-0.86**	0.33
Number of slaughtershouses	0.45**	0.20	0.50**	0.19
Soy area in 2006	0.79**	0.13	0.70**	0.25
Precipitation	0.04	0.08	-0.27	0.51
Temperature	0.02	0.08	0.19	0.14
Presence of Embrapa experiments	0.85**	0.30	1.49**	0.54
Technical assistance	-0.02	0.07	-0.29	0.23
Zm_Per capita GDP	NA		0.22	0.36
Zs_Average farm size			0.04	0.13
Zm_Average land price			0.04	0.17
Zm_Average soy productivity			0.05	0.25
Zs_Cooperative membership			-0.70	0.22
Zs_Soy Area in 2006			0.30	0.28
Zm_Precipitation			0.30	0.51
Zm_Temperature			-0.09	0.13
Zs_Presence Embrapa			-0.27	0.14
Zm_Percentage of farmers with technical assistance			0.288	0.227

Post-hoc Tukey's tests (Table 4.7) further showed that counties with iCL are not significantly different than soy dominant counties except for when it comes to the presence of slaughterhouses (which are more numerous among the first group). At the same time, important differences exist between iCL counties and pasture dominant counties with respect to *per capita* GDP, presence of Embrapa experiments and historical soy area – which are all significantly higher in iCL counties.

*Table 4.7. Tukey's pairwise comparison of means with equal variance. County groups "iCL", "Pa" and "Cr" refer, respectively, to counties with iCL, counties with pasture but no iCL, and counties with soy only. **P<0.01.*

County variable	Groups	Contrast	Std. Err.
Per capita GDP	Pa vs iCL	-0.70**	0.19
	So vs iCL	0.27	0.31
	So vs Pa	0.97**	0.29
Number of slaughterhouses	Pa vs iCL	-0.13	0.07
	So vs iCL	-0.29*	0.12
	So vs Pa	-0.17	0.12
Presence of Amaggi Group	Pa vs iCL	-0.04	0.03
	So vs iCL	0.029	0.05
	So vs Pa	0.06	0.05
Presence of Embrapa experiments	Pa vs iCL	-0.16**	0.05
	So vs iCL	-0.09	0.08
	So vs Pa	0.06	0.07
Soy area in 2006	Pa vs iCL	-0.99**	0.18
	So vs iCL	-0.10	0.29
	So vs Pa	0.89**	0.27

4.5. Discussion

4.5.1. Information access

Farmers and ranchers make management decisions constantly and may move in and out of crop-livestock integration either gradually or abruptly given the flexibility of this production system (Alves et al., 2015). In that sense, a household starting integration in a small share of their land might be similar to a specialized producer and vastly different from someone farther along the scale of integration. Nevertheless, our results highlighted important contrasts between the three groups at this point of the iCL diffusion process in Mato Grosso, including iCL adopters' higher education level and better access to technical assistance. Although iCL adopters form a distinct and sometimes consistent group, our results indicate that they are more similar to soy producers and less similar to ranchers – particularly in terms of risk perceptions and investment preferences.

The proximity between iCLs and Embrapa experiments observed at the county level reveals the importance of pilot initiatives that create knowledge and facilitate farmers' exposure to new technologies. Both contribute to improve access to information and reduce risks associated to innovations, ultimately increasing their uptake.

The difference in education across groups supports hypotheses that better educated households are more open to innovations (Feder & Umali, 1993; Sunding & Zilberman, 2001). This finding is noteworthy in our case given how little variation exists in education amongst rural producers in Mato Grosso (IBGE, 2006). It also underscores the potential importance of farm succession for the adoption of particular management practices (Ingram et al., 2013). The transition from specialized to integrated systems is often initiated by younger generations, mostly the sons of landowners who go to urban areas to get formal training in agronomy or animal sciences. Without these younger generations, farmers are often unaware or unmotivated to change their practices to increase productivity (Inwood & Sharp, 2012).

Farmers' geographic and cultural backgrounds are also important for iCL adoption. Many of the farmers who migrated to Mato Grosso from Southern Brazil have a long history of crop farming region, while farmers born in the Center-west have a higher exposure to beef cattle rearing (Jepson, 2006). These cultural aspects create differences in informal knowledge among the producers in Mato Grosso and may also explain divergent preferences related to risk and complexity, which directly influence the adoption of complex agricultural systems (Hardaker et al., 2004). These reinforcing feedback loops between culture, land use, and risk perceptions create inertia with respect to innovations even when economic and environmental advantages may accrue from them (Pannel et al., 2006). Overcoming this inertia requires copious information and evidence about the benefits of a new technology, explaining the significance of proximity to experimental farms in our analysis and the clustering of iCL adoption.

4.5.2. Supply chain infrastructure

The clustering of iCL farms around existing soy production regions and slaughterhouses underscores the importance of adequate supply chain infrastructure for both the crop and livestock aspects for iCL adoption. This infrastructure is necessary to provide the inputs and equipment for production, as well as processing activities required for long distance transport and export (Porter, 2000; Brady & Irwin, 2011; Garrett et al., 2013b).

The relative similarity between “iCL” and “So” revealed by the Tukey’s test is related to the stricter infrastructure, logistics and management requirements of crop farming relative to those of ranching. For example, the absence of storage facilities does not pose problems for ranchers but may be a constraint to soy farming since soybeans must be dried, weighed, and checked for quality within a close proximity to where they are grown (Loewer et al., 1994). Still, the fact that iCL counties are significantly different from soy counties in terms of number of slaughterhouses (which are more numerous among iCL counties) offers evidence that the proximity to farming might be a necessary but insufficient condition for the establishment of iCL.

Finally, the negative relationship between iCL adoption and the Amaggi Group presence is worth pointing out. Although iCL adoption could further improve Amaggi Group’s image of environmentally responsible soybean producer in European markets, the opportunity costs of iCL adoption (versus specialized soybean production) may be too high (Garrett et al., 2013b).

4.5.3. **Capital availability**

The transition from a specialized to an integrated system almost always involves costs. The negative relationship between households’ level of indebtedness and iCL adoption suggests that early adopters of iCL are usually well-established and have already paid off other debts they may have acquired in the process of establishing themselves by the time they decide to engage in a new enterprise. Given that iCL adoption is more common among ranchers than farmers, iCL adopters’ lower levels of indebtedness might also be explained by ranchers’ risk-averse profile and lower reliance on external financing sources relative to soybean farmers (Gil et al., 2015). At the county level, the fact that *per capita* GDP of counties with iCL was not significantly different from that of soy dominant counties reveals that iCL adoption has been more common in wealthier regions of Mato Grosso.

The apparent irrelevance of credit for iCL adoption may be partly explained by its poor geographic allocation, bureaucracy, and unpreparedness of bank agents responsible for issuing the credit, as identified by other preliminary assessments of the ABC Plan (SENAR, 2013; IPAM, 2015). Where credit is available, the absence of infrastructure and information poses barriers to iCL adoption, indicating that interventions exclusively based on credit provision are not sufficient to ensure wide-scale adoption of complex agricultural innovations.

4.5.4. **Labor**

The literature offers contrasting evidence concerning labor demands of mixed versus specialized production systems. On the one hand, integration may demand less labor in cases where interactions between systems' components lead to increased labor efficiency (i.e. the amount of calories produced per unit of labor may increase disproportionately relative to the amount of labor needed) or reduced per-unit cost of labor during peak labor demand periods (Hoekstra, 1987; Lee, 2005). On the other hand, the combination of crop and livestock activities may pose continuous labor requirements (Thornton & Herrero, 2015). In fact, some studies conducted in Brazil have showed that mixed systems have higher labor demands globally and/or seasonally, and that labor costs may profoundly influence management decisions (De Souza Filho et al., 1999; Caviglia & Kahn, 2001).

Our analysis showed no significant association between iCL adoption and labor availability (represented in our model by the number of farm workers at the household level). The fact that producers engaging in iCL often do not use their current labor resources to the full extent and may be able to do so without hiring extra labor (Gil et al., 2015) makes such assessment challenging. Farmers may also train their employees and/or rely on technical advice from third parties when specialized expertise is required instead of hiring qualified labor (e.g. private consultants, peers, input suppliers and research institutions).

It is important to consider that iCL systems in Mato Grosso are usually applied at a large-scale and are less labor-intensive than the mixed systems usually practiced by smallholders, involving mechanized farming and free-range ranching. By incorporating cattle into a farming system or crops into a ranching system, labor demands may not increase as much as the amount of calories produced per unit of labor. Still, an accurate assessment of the labor requirements of the iCL systems practiced in Mato Grosso would require estimates of regular and specialized labor needs as well as the calculation of yield gaps for each agricultural system over their implementation and maintenance phases.

4.5.5. **Strengths, limitations and future research**

Whereas the use of data aggregated at the county level allows for the incorporation of a larger geographical surface as well as certain infrastructural variables that cannot be as easily captured at the household level, it also entails "simplifying assumptions about the homogeneity of the decision makers and the dynamics comprising that aggregate" (Lesschen et al., 2005, p. 22). The use of household data in our analysis complements the county level analysis by revealing the importance of individual preferences and knowledge for changing agricultural behavior and by highlighting the diversity among rural producers. Although iCL diffusion depends on specific individual and regional conditions, our analysis suggests that early adoption of iCL might be explained primarily by household characteristics, while its broader dissemination will ultimately depend on regional constraints.

Analyzing the farm and county scales simultaneously also allows us to examine the interplay between constraints and incentives at different scales, highlights interesting areas of convergence, and enhances understanding of the generalizability of results between scales. This approach allows for policy recommendations that can be better targeted and/or tailored to individual objectives. For instance, focus could be placed on farmers or regions that are most likely to adopt iCL with only a small adjustment in policy as opposed to those that require a more transformative change.

Nevertheless, these results should be interpreted carefully. First, the small number of current iCL adopters poses an obstacle to the detailed examination of adoption determinants between different types of iCL. For example, one might expect distance to roads or access to credit to influence the adoption of more complex iCL systems differently given their unique implementation and maintenance requirements, yields, and management operations. Second, our data clearly captures early adopters who do not always follow a pattern representative of broader adoption (Rogers, 2003). The monitoring of the iCL dissemination process over a longer period of time would allow us to check whether the factors associated to iCL occurrence change and what influence county development has on innovation adoption decisions. That is also relevant for making inferences about the likelihood of innovation adoption based on farmers' profiles. Additional research avenues include the investigation of labor requirements of specialized versus integrated systems as practiced in Mato Grosso, as well as the effect of the distance to supply chain infrastructure elements on the costs and benefits of iCL.

4.6. Conclusions

By investigating the socioeconomic profile of iCL adopters and several characteristics of places where iCL systems occur, we gained insights into individual and regional factors associated with iCL dissemination and their influence on the diffusion of these systems in Mato Grosso. Though the iCL diffusion process in the state is recent and dynamic, we found that access to information, education, and culture are the most important factors for iCL adoption at the household level, while supply chain infrastructure for soy and cattle, as well as proximity to iCL experiments, are the most important factors at the county level.

Our study offers valuable and straightforward insights for land use policy. First, it highlights the need to invest in improved education and technical assistance related to iCL. Besides trainings and capacity building among technicians, the establishment of social networks and the multiplication of field experiments such as the ones currently conducted by Embrapa could increase exposure to the new technology. Each of these actions should not only address the complexity of iCL systems but also be tailored to farmers and ranchers according to specific aspects of iCL with which each group is less familiar. Second, the concentration of iCL near soy areas reveals the need to promote iCL more strongly in regions dominated by pasture if the Brazilian Government's goal to restore degraded lands and intensify are to be achieved. This could be done by offering incentives such as tax exemption and credit to supply chain actors that establish themselves in key locations. Partnerships between ranchers and farmers constitute another promising alternative to scale up iCL adoption while also ensuring the engagement of both groups in the transition from a specialized to an integrated agriculture. Instead of having rotation of crops and grasses across different plots within the same farm, rotation could be established among two properties (e.g. cattle would be shifted from one to the other periodically, so that both are farmed and grazed). This would ensure mutual benefits for farmers and ranchers, particularly knowledge exchange and cost sharing with respect to the acquisition of machinery and animals. The current increase in the number of land rental contracts in Mato Grosso involving the temporary conversion of pastures into cropland (Cohn et al., *in review*) could help bring ranchers and farmers together. Third, the irrelevance of the ABC credit for iCL adoption reveals the need to assess the effectiveness of the ABC Program. If target at less capitalized producers or at places father away from existing agricultural hubs (where production costs tend to be higher), credit could possibly make a difference in promoting iCL. However, even in that case, credit provision will have to be combined with other individual and regional conditions.

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4.9. Appendix 1 –Variables used for the household- and county-level analyses

Table A 4.1. Results of collinearity tests for variables analyzed at the household level.

Variable	VIF	1/VIF
Farm ownership status	1.32	0.760215
External financing sources	1.56	0.642322
Level of indebtedness	1.91	0.523767
Total farm size	1.56	0.641471
Double cropping	1.98	0.504985
Distance to the nearest road	1.51	0.66195
Farm topography - flat	3.21	0.3115
Presence of sandy soils	1.26	0.79584
Number of farm workers	1.99	0.503198
Education level	1.2	0.836073
Access to sector information	1.08	0.928949
Access to technical assistance	1.39	0.720819
Participation in networks	1.25	0.799826
Region of origin - South	1.31	0.762839
Mean VIF	1.66	

Table A 4.2. Results of collinearity tests for variables analyzed at the county-level.

Variable	VIF	1/VIF
Per Capita GDP	2.41	0.41491
Presence of credit union offices	1.13	0.888252
Access to ABC loans	1.08	0.927007
Average farm size	1.72	0.58287
Average land price	1.63	0.614043
Average soy productivity	1.33	0.754527
Cooperative membership levels	2.58	0.387771
Presence of Amaggi Group	1.48	0.67351
Number of slaughtershouses	1.3	0.768429
Soy area in 2006	3.93	0.25413
Precipitation	1.29	0.772994
Temperature	1.35	0.741094
Presence of Embrapa experiments	1.17	0.852924
Technical assistance	1.15	0.869753
Mean VIF	1.71	

4.10. Appendix 2 – Spatial auto-correlation tests with variables explored at the county-level

Table A 4.3. Descriptive statistics of spatial control variables used at the county-level regression.

Spatial control variables	Description	Mean	Std.Dev.	Min	Max
Zm_Per capita GDP	mean	-0.0123	1.0071	-1.7403	4.5770
Zs_Average farm size	sum	-0.0061	0.9990	-0.8548	5.4407
Zm_Average land price	mean	-0.0181	1.0194	-2.5568	2.0588
Zm_Average soy productivity	mean	-0.0187	1.0210	-2.6418	1.6539
Zs_Cooperative membership	sum	-0.0022	0.9968	-0.3163	6.9992
Zs_Soy Area in 2006	sum	-0.0031	0.9971	-0.4416	5.6556
Zm_Precipitation	mean	-0.0574	1.2075	-8.0989	1.8506
Zm_Temperature	mean	-0.2065	2.6467	-29.1154	2.3024
Zs_Presence Embrapa	sum	-0.0019	0.9967	-0.2695	6.8688
Zm_Percentage of farmers with technical assistance	mean	-0.0143	1.0109	-2.0218	3.4138

Table A 4.4. Results of a Moran's I test with variables of the regression model. The dependent variable ("#iCL in each county") and ten IVs are spatially auto-correlated at a 0.5 significance level.

Variables	I	E(I)	sd(I)	z	p-value*
# iCL in each county	0.025	-0.007	0.013	2.539	0.006**
Per Capita GDP	0.037	-0.007	0.013	3.392	0.000**
Presence of credit union offices	-0.01	-0.007	0.009	-0.342	0.366
Access to ABC loans	-0.006	-0.007	0.014	0.078	0.469
Average farm size	0.045	-0.007	0.013	3.96	0.000**
Average land price	0.232	-0.007	0.014	17.531	0.000**
Average soy productivity	0.097	-0.007	0.014	7.641	0.000**
Cooperative membership levels	0.047	-0.007	0.013	4.281	0.000**
Presence of Amaggi Group	-0.005	-0.007	0.011	0.221	0.413
Number of slaughtershouses	0.005	-0.007	0.013	0.961	0.168
Soy area in 2006	0.059	-0.007	0.013	5.178	0.000**
Precipitation	0.345	-0.007	0.014	25.899	0.000**
Temperature	0.116	-0.007	0.014	9.097	0.000**
Presence of Embrapa experiments	0.014	-0.007	0.013	1.702	0.044*
Technical assistance	0.016	-0.007	0.013	1.694	0.045*

Table A 4.5. Results of spatial error and spatial lag tests with the regression model as a whole.

Test		Statistic	df	p-value
Spatial error	Moran's I	0.62	1	0.535
	Lagrange mult.	0.111	1	0.739
	Robust mult.	0.009	1	0.925
Spatial lag	Lagrange mult.	0.104	1	0.747
	Robust Lagrange mult.	0.002	1	0.965

4.11. Appendix 3 – Details on the country sorting procedure and MANOVA results used in the county-level analysis

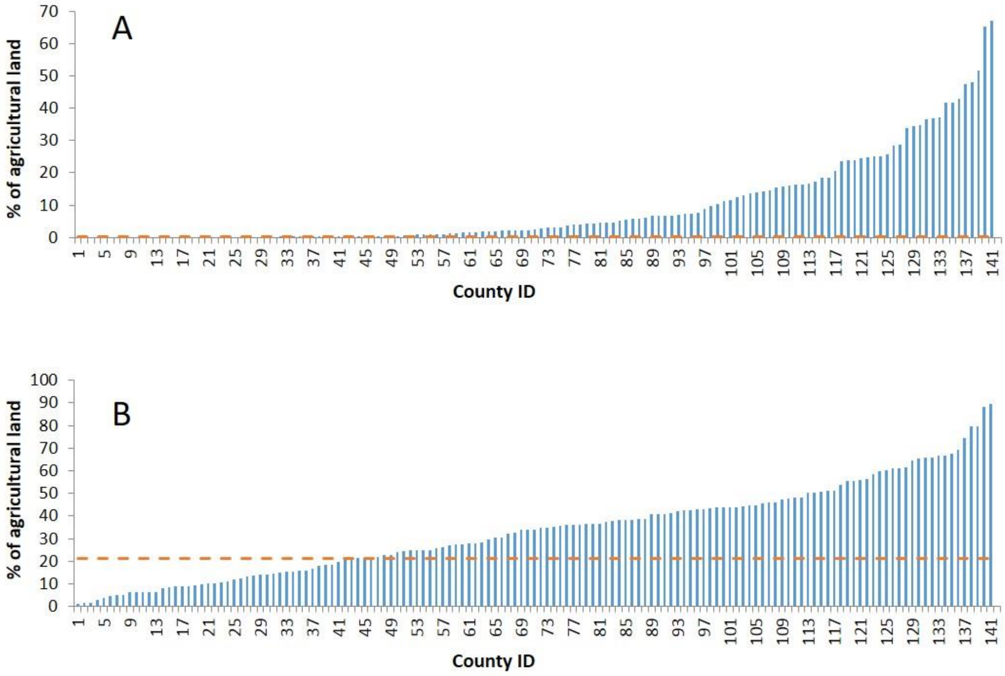

Figure A 4.1. Share of total agricultural land (%) dedicated to soy (A) and pasture (B) in each county. Only counties above the cut-off point (30th percentile) represented by the dashed line were considered in the analysis.

Table A 4.6. Soy and pasture indicators correspondent to the cut-off point used to group counties for the second part of the spatial analysis at the county-level.

	Soy	Pasture
Percentile	0.3	0.3
% of area cutoff in each municipality	0.1965	21.3259
% of MT's total soy/pasture area cutoff	0.2	18.6
MT's soy/pasture land (ha) cutoff	12553	4111576

*Table A 4.7. Results of four MANOVA tests with 132 counties. For each test, F statistics and associated p-values are also displayed. ** P>0.01.*

Test	Statistic	df	F(df1,	df2)	F	Prob>F
Wilks' lambda	0.5155	2	30	230	3.01	0.000**
Pillai's trace	0.5416		30	232	2.87	0.000**
Lawley-Hotelling trace	0.8289		30	228	3.15	0.000**
Roy's largest root	0.6612		15	116	5.11	0.000**

5. 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 submitted to *Regional Environmental Change* in December 2015.

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 (ABC Plan) to finance investments into 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 the agent-based simulation package MPMAS together with the crop simulator MONICA 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 credit lines of the ABC Plan through indicators such as land use change, adoption rates and budgetary costs of credit provision. Our findings show that the efficiency and effectiveness of ABC credit could be enhanced through changes in maximum amount that farmers are allowed to borrow, interest rate and access to teak markets, while also highlighting that credit provision alone will hardly ensure switching to low-carbon agriculture in Mato Grosso. Sensitivity analyses reveal that specific credit conditions might speed up the diffusion of low-carbon agricultural systems in Mato Grosso, particularly among medium-size farmers.

5.1. Introduction

Brazil is aware of its great responsibility to combat climate change. During the 15th Conference of the Parties (COP15), the country pledged to take domestic actions to substantially decrease its green-house gas (GHG) emissions. According to this pledge, national emissions shall be reduced by 36.1–38.9% until 2020. As a consequence, a major mitigation effort must be made in the agriculture and land use sectors, which currently account for more than 60% of Brazil's annual GHG emissions (Brazil 2016). Agriculture alone is expected to reduce 166 million tons of CO2eq, or 43% of the national mitigation efforts by 2020 (World Bank 2010; Soares Filho et al. 2011; Mozzer 2012). However, this should not undermine the sector`s great economic and political importance.

Brazil aims to simultaneously ensure climate change mitigation and economic development by offering farmers incentives to switch to low-carbon agricultural practices. The ABC Credit Program, launched in 2010 as part of the Federal Government's Low-Carbon Agriculture Plan ("ABC Plan"), supports the adoption of low carbon land use systems, such as commercial forest plantations and integrated crop-livestock-forestry systems, by providing preferential loans to their adopters. The impacts of this program, however, are yet unclear. Existing studies either conduct only cost analyses based on data from a single farm (de Oliveira Silva et al. 2015) or investment analyses of single production alternatives (Bezerra et al. 2011; FAMATO 2013). What is missing is a holistic analysis able to compare low-carbon land use options with conventional ones, while taking into account the heterogeneity of local farms in terms of resource endowments, investment opportunities, as well as environmental, technical and market conditions.

The present article addresses this knowledge gap by conducting a quantitative assessment of farm systems in the state of Mato Grosso. Over the last decades, Mato Grosso has developed a highly dynamic, export-oriented agricultural sector, mainly based on large-scale soybean and cattle production, which has led to vast clearing of rainforest and savanna vegetation, as well as significant GHG emissions (Morton et al. 2006; Fearnside et al. 2009; DeFries et al. 2013). For our integrated assessment, we apply bioeconomic microsimulation, integrating the software packages MPMAS and MONICA. The model set-up, parameterization and validation are described in the following sections. Our simulation results provide detailed information on the effectiveness and efficiency of the ABC Credit Program in supporting the adoption of low-carbon agricultural systems. Through computer simulations we evaluate current and alternative ABC credit lines in Mato Grosso and offer suggestions for their implementation.

5.2. Background information

5.2.1. Research setting and objectives

This study was conducted within the research project "Carbon sequestration, biodiversity and social structures in Southern Amazonia: models and implementation of carbon-optimized land management strategies (CarBioCial)" funded by the German Federal Ministry of Education and Research. The project particularly aims to assess on-farm trade-offs between different land use options and to identify policies that could effectively support the diffusion of low-carbon land use systems in the state of Mato Grosso. This paper specifically analyzes the adoption of commercial tree plantations and integrated systems of crop, livestock and forestry in Mato Grosso, supported by the ABC Program. It addresses three central research questions: first, whether these production practices are able to generate farm-income levels comparable to those provided by the currently predominant soybean-maize and soybean-cotton double-cropping systems; second, how the provided preferential credit lines (i.e. ABC Integration and ABC Forests) affect local land use decisions; and third, how the land use choices may change with respect to changes in the prices of agricultural products and the conditions of ABC credit lines. The ultimate objective of this study is to conduct a modeling-based quantitative assessment of agricultural production in Mato Grosso. The assessment has is done at the farm level, explicitly accounting for individual resource and operational constraints (e.g. limited amount of own capital, crop rotation requirements, inter-temporal machinery and labor allocation, and land availability). At the same time, it considers the resource differences between farms as well as inter-regional differences in climatic and market conditions.

5.2.2. Study Area

Mato Grosso is the third largest state of Brazil by area occupying 903,000 km^2 (IBGE, 2013). Since the 1970's, Mato Grosso experienced a huge expansion of agricultural and pasture lands coupled with deforestation of the savanna and rainforest biomes (DeFries et al., 2013). rom 1990 till 2013, the area allocated to crop production increased fivefold, or by 10 million hectares (IBGE, 2013). In 2004, the annual deforestation rates in Mato Grosso reached a historical peak at 11,800 km^2 (INPE, 2015). Deforestation has significantly decreased since then, yet remaining land clearance and subsequent soil tillage still cause large amounts of greenhouse gas emissions (Galford et al., 2011). Good climatic conditions allowing for two growing seasons, together with the introduction of improved seeds and techniques for soil acidity correction 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 for 52% of the national cotton production (IBGE, 2013). Cattle ranching is another prominent farming activity in the state, with the local herd size estimated to consist of 28 million heads (IBGE, 2013). The vast majority is beef cattle of *Nelore* and *Angus* breeds, grazing at stocking rates of 0.1 to 1.4 animal units per hectare (FNP, 2014).

The bulk of Mato Grosso's agricultural output is produced in five of the seven macro-regions of the state, as classified by Mato Grosso Institute of Agricultural Economics (IMEA). These regions also comprise our study areas: Mid-North, North East, South East, Central South and West. Together they extend over about two thirds of the state's territory and are subject to regular collection and publication of farm operational data by IMEA.

5.2.3. **ABC program and credit lines**

As a pillar of Brazil's strategy for GHG mitigation, the National Plan of Low Carbon Emission in Agriculture (ABC Plan) seeks to stimulate the adoption of low-carbon agricultural practices. The ABC Program is the credit component of the ABC Plan. It offers preferential loans to farmers for implementing one or several of the following agricultural practices: (i) industrial forestry plantations, (ii) integrated systems of crops, livestock and forestry, (iii) restoration of degraded pastures, (iv) no-till farming, (v) biological nitrogen fixation and (vi) treatment of animal waste (MAPA, 2012).

The first two practices (forest plantation and integrated systems) are relatively new in Mato Grosso and offer alternatives to the common production systems – including soybean and maize double-cropping, soybean and cotton double-cropping, soybean mono-cropping, cotton mono-cropping and extensive cattle ranching. For both, forest plantations and integrated systems, the ABC Program offers specific credit lines: *ABC Integration* for integrated systems and *ABC Forests* for plantations. The motivations to support these enterprises are many. First, forest plantations (either standalone or as part of an integrated system) increase wood and energy supply and thereby reduce pressure on natural forest areas (IMEA, 2013a). Second, forest plantations contribute to carbon sequestration. Third, integration of crops and livestock may increase returns per hectare and, therefore, spare land (Cohn et al., 2014; Strassburg et al., 2014). And fourth, the interaction between crops, livestock and forests may increase crop yields and livestock output (Assmann et al., 2003).

The conditions of the credit lines that correspond to these two practices – ABC Forests and ABC Integration – are generally similar (see Table 5.1). The annual interest rate for both is 5% (AGRIS, 2015). This is a very lucrative opportunity, considering that the interest rate of the central bank currently equals 14.25% (BACEN, 2015). The maximum amount fundable, the grace period and the payback period are higher for ABC Forests. Still, the official documentation (AGRIS, 2015) lacks a clear definition of what is considered as a forested area in integrated systems. According to our discussions with local experts, the common practice is to use the lower bound of canopy specified in IPCC (2015), which equals to 10%. This means that a system with one hectare of forest will be recognized as a ten-hectare integrated system. In integrated systems with cattle, frequency of rotation varies, 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 forest, for the systems with cattle the criterion is also unclear. According to local bank representatives, in practice, the banks check whether the land is allocated to an alternative use (either crop farming or cattle grazing).

Table 5.1. Conditions of ABC credit lines

	ABC Integration	ABC Forests
Supported enterprise	Integrated systems of crop/livestock, crop/forestry and crop/livestock/forestry	Industrial tree plantations (eucalyptus, teak, oil palm, mahogany, oak, etc)
Fundable amount	2 MM BRL[a]; up to 40% of investment costs, if cattle are involved, otherwise – 30%	3 MM BRL; up to 35% of investment costs
Annual interest rates	5%	5%
Payback period	8 years for crop-livestock systems and 12 years when forest is involved	12 – 15 years depending on the tree species[b]
Grace period	3 years	8 years, but repayment has to be made within 6 months after the first forest harvest
Additional financing	–	Seeds nursery can be funded[c]

Source: Banco do Brasil (2015), BNDES (2015)
a – 1 Brazilian Real (BRL) equals 0.33 USD in 2015 (source: www.oanda.de);
b – For oil palm trees (*Elaeis guineensis*) the loan must be repaid within 12 years and the grace period in this case is 5 years;
c – This part of the project has a payback period of 5 years and a grace period of 2 years.

5.3. Methods and data

5.3.1. Methodology

We applied integrated micro-simulation modeling (Troost et al., 2015; Wossen &

Berger, 2015; Ewert et al., 2009; Piorr et al., 2009) for our assessments of low-carbon land uses and the impacts of ABC credit lines. This approach has several benefits over investment analysis or gross margin comparison of single production options, which are commonly used in assessments of new agricultural production alternatives. First, farm-based modeling integrates all possible production alternatives in one mathematical programming matrix, and thus internalizes operational and investment constraints of the farm. In conventional methods based on separate per hectare calculations for single alternatives (e.g. comparison of gross margins), these important and sometimes binding constraints, for example total labor available on farm, are not considered. Second, the approach allows simulating a heterogeneous population of real-world farms through computational model agents, which enables up-scaling the assessment results from farm level to the level of municipalities and macro-regions and renders the results applicable for different farm types. Third, the integration with a processed-based crop growth model allows for capturing the effects of climate, soil and management (i.e. choice of fertilization, seed maturity group as well as planting and harvesting dates) on crop yields. Fourth, the dynamic implementation of a simulation model allows modeling the temporal development of farm physical and financial assets. Therefore, the long-term impacts on farm structure and capital can be assessed.

5.3.2. **Model overview**

We implemented our simulation in MPMAS, a multi-agent software package developed for simulating farm-based economic behavior and human-environment interactions in agriculture (Schreinemachers & Berger, 2011). This software has been applied in a number of studies focusing on innovation diffusion in agriculture (Schreinemachers et al., 2009; Schreinemachers et al., 2010; Marohn et al., 2013; Quang et al., 2014) as well as for integrated assessments of farm-level agricultural policies (Troost et al., 2015; Wossen & Berger, 2015). For modeling the decisions of farm agents, MPMAS employs mathematical programming. The article of Schreinemachers & Berger (2011) describes the software architecture and equations of MPMAS following the ODD-protocol. Technical documentations, executable programs and software manuals are available for download from the developer's website: *https://mp-mas.uni-hohenheim.de*.

For our research on low-carbon agriculture in Mato Grosso, we developed a specific application of MPMAS. The agent decision-making module of this application was parameterized for the common farming enterprises in the study area: soybean, cotton, maize, cattle, eucalyptus and teak production. The objective function of the agent decision problems considers the expected farm income, which has to be maximized subject to a set of constraints, specified in the form of equations or inequalities. In every simulation period of the model, which corresponds to one real-world agricultural year, agents take two decisions: an investment decision and a production decision. During the investment decision stage, each agent decides in which durable assets (e.g. machinery, tree plantations) to invest. The investment decision is taken based on the values of resource requirements, prices and yields expected in the long-run. Assets can be purchased both on loan and with full self-financing. In the production decision stage, the agent sets up the operational plan for the current period. This decision is taken based on resource requirements, prices and yields expected for that period, adding possible new assets purchased as part of the agent investment decision. MPMAS then computes the individual performance (e.g. income, cash flow) of the agent, based on the actual prices and yields, and updates its liquid and physical assets and liabilities. The resulting values for each agent are finally carried over to the next simulation period as initial values for the subsequent investment and production decisions. In total, the agent optimization problem for the investment decision contains 3,819 decision variables (including 150 integer variables) and 3,887 constraints, while the optimization problem for the production decision contains 3,755 decision variables (90 integers) and 3,886 constraints.

The crop yields for the various production alternatives were simulated by the process-based biophysical simulator MONICA (Nendel et al., 2011), which has been specifically parameterized and calibrated by its developers for the study area conditions during the CarBioCial project. The site-specific crop yields were simulated with MONICA for all soybean, cotton and maize production alternatives implemented in MPMAS using 2000-2013 weather data. Simulated crop yields and other model parameters are stored on the MySQL-server. We set up a database application (called mpmasql), which accesses the database and converts the stored parameters into input for MPMAS. The MPMAS application then can be run either on a personal computer or on a computer cluster. For simulating agent decisions, the application uses COIN's CBC mixed-integer programming solver, which we fine-tuned for this study.

5.3.3. **Model parameterization**

We parameterized our MPMAS application for five municipalities of Mato Grosso: *Canarana*, *Campo Verde*, *Sapezal*, *Sorriso* and *Tangara da Serra*. These municipalities are considered by IMEA as representative of the corresponding macro-regions (listed in section 5.2.2). During various rounds of data collection, IMEA approached selected farmers from these municipalities and compiled detailed data on farm assets and crop production activities. We used this data (IMEA, 2013b) together with expert knowledge and the crop-level dataset of a private consultancy in Brazil (Celeres, 2013) for setting-up crop production requirements in our application. Prices for inputs, transportation, processing costs, wages for hired labor, information on taxes as well as data on credit sources and conditions were also taken from IMEA (2013b), while municipality-specific time-series of prices for agricultural products were obtained from the online price database of IMEA (2015). Purchase prices for agricultural machinery were taken from local traders, while operational costs of machinery were estimated using the methodology of CONAB (2010).

The agent population includes all crop-producing farms in the five municipalities, which were larger than 50 hectares in total area, according to the latest agricultural census data available (IBGE, 2006). At the time of the census, these 844 farms constituted 74% of all crop-producing farms in the municipalities in terms of number and 99% in terms of agricultural area. Using the empirical data of IBGE (2006), IBGE (2013) and IMEA (2013b), we created multiple statistically consistent populations of model agents (844 agents in each population) following the Monte Carlo approach of Berger & Schreinemachers (2006). Information on soils was taken from the geo-referenced soil database of Brazil (Muniz et al, 2011) and from SEPLAN (2011).

5.3.4. **Modeling forest plantations, livestock and integrated systems**

In MPMAS, we implemented four types of forestry systems: three with eucalyptus (*Eucalyptus urograndis*) and one with teak (*Tectona grandis*). The first eucalyptus system is for charcoal production with a 7-year production cycle. The model parameters for this system, such as investment costs, labor and machinery requirements and charcoal output, were estimated from IMEA (2013a). The second eucalyptus system is for mixed use (charcoal and wood) with a 12-year production cycle, also estimated from IMEA (2013). The third system is a wood-only eucalyptus seedling and coppicing double-planting regime with a 14-year production cycle, based on Rode et al. (2014). Finally, for teak we implemented a production system with a 20-year cycle, described by 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 (SEAB, 2015). The risk premium for discounting future values of forest investments in our analysis is equal to 4.9%. This risk premium is commonly chosen for the analysis agricultural investments in Brazil by the local banks. It is estimated as JPMorgan Emerging Markets Bond Index Plus for Brazil adjusted for the agricultural sector by multiplying the index with the beta coefficient[9] of the agricultural companies listed at the Bovespa stock exchange.

For the definition of cattle production alternatives, we used data on livestock systems from Anualpec 2013 (FNP, 2014). In total, our MPMAS model contains 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 provided by Anualpec 2013 (FNP, 2014).

Integrated systems in MPMAS are defined as combinations of crops, livestock and forests on the same plot. Generally, they could be classified into crop-livestock, crop-forestry, livestock-forestry or crop-livestock-forestry systems. Experiment-based studies on the biophysical interactions between crops and livestock in integrated systems are mostly based on non-comparable conditions and often present contrasting evidence as to their effect on overall productivity. Besides, to the best of our knowledge, no results are available for integrated systems containing forestry in Mato Grosso. Still, the few existing studies on crop-livestock interactions conducted in conditions similar to our study area have presented only short-term effects (see da Silva et al., 2012; Flores et al., 2007; Kunrath et al., 2015 and Landers, 2007). In general, the results of these studies suggest that in terms of profitability of the systems, the magnitude of the short-term effects is minimal. Given the described lack of consistent evidence on interaction effects, we have therefore neglected interaction effects in our present model implementation. The implementation of ABC Integration and ABC Forests credit lines was based on the official regulations of the ABC Program (AGRIS, 2015) released by BNDES (summarized in Table 5.1).

5.3.5. **Model validation**

The common way to empirically validate economic micro-simulation models is to compare the values of the model output variables with the corresponding statistics from the real world (Fagiolo et al., 2007). For the validation of this MPMAS application, we used two benchmarks: IMEA (2013b) data of single farms for the farm-level validation and IBGE (2013) municipality land use data for the municipality-level validation. In other words, we carried out two separate validations with the same model, which is necessary, given that the model

[9] Beta coefficient is a measure of the volatility, or systematic risk, of a security or a portfolio in comparison to the market as a whole.

simulates both, the behavior of individual farms and that of the study area as a whole.

During the farm-level validation procedure, we inserted the farm profiles (i.e. information on land ownership, asset endowments and location characteristics) specified in IMEA (2013b) as model input and let the model simulate the land use of these farms. Then, we compared the simulated land use (by crop and season) with the land use recorded in IMEA (2013b) and calculated the model efficiency using the Nash-Sutcliffe formula[10]:

$$ME = 1 - \frac{\sum_{i=1}^{n}(Q_o^i - Q_s^i)}{\sum_{i=1}^{n}(Q_o^i - \overline{Q_o})}$$

where Q_o^i – observed value in *i*-case; Q_s^i – corresponding *i*-case value simulated by a model; $\overline{Q_o}$ – mean over all observed values.

On the farm-level, our application has a model efficiency of 0.75, which is a good result. During 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, the model efficiency improves to 0.93. Figure 5.1 depicts scatter plots of observed and simulated results for both validation levels. The fitted no-constant regression lines and their calculated R-squared (0.86 for the farm level and 0.99 for the municipality level) indicate the good fit of the model results. The slope coefficient of the regression lines for the farm level equals to 0.81, which means that the model underestimates the areas of cropland by 19% in the aggregate. 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% in the aggregate, which stems from overestimating the land use share of cotton. In general, the results of the empirical validation suggest that our MPMAS model is able to simulate land use decisions consistently at farm-level and accurately at municipality level.

[10] In this specification of the equation, the model errors are compared with errors caused by using the sample mean as a prediction tool. Respectively, the efficiency of one indicates a perfect match between the simulated data and the observed data and the efficiency smaller than zero indicates that the sample mean is the better predictor than the model.

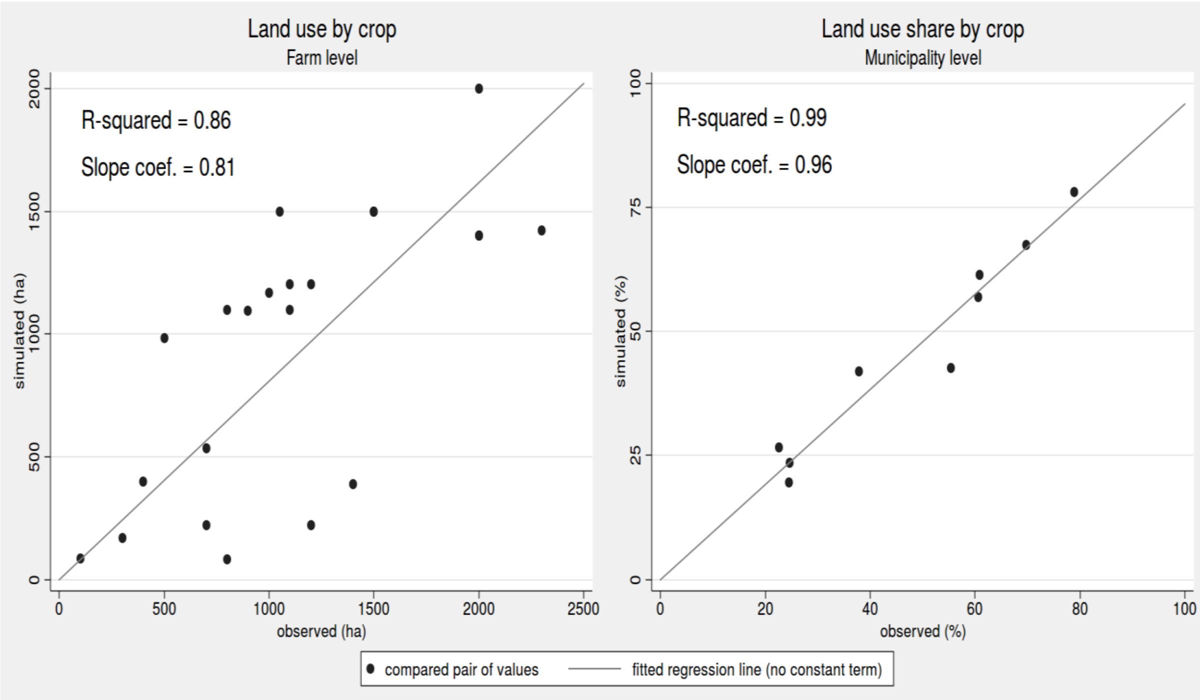

Figure 5.1. Model validation. Based on MPMAS simulation results for baseline scenario after one simulation period.

The crop growth model MONICA was validated for Mato Grosso's soil and climatic conditions by Hampf et al. (*in preparation*) using the crop yield estimates from IBGE (2013) online database. The crop yields of soybean, maize and cotton that had been simulated with the MONICA model (and later integrated in MPMAS) were compared with the average yields of the years 2000 – 2013.

Figure 5.2 shows such a comparison for one of the study municipalities (Sapezal). As can be seen from the figure, the empirical average in the vast majority of the cases lies within the range of yields simulated with MONICA. The range of predictions corresponds to the possible crop-growing practices that have been used in the study area. Overall, the validation of the crop growth model suggests that its predictions match the municipality-level average yields, and the direction of the yield responses in different climate years match as well. However, it was not possible to validate the farm-level prediction of the crop growth model, due to lack of yield and crop management data disaggregated at the level of individual farms. We plan to perform this farm-level validation of crop yields, once the necessary benchmark data has become available.

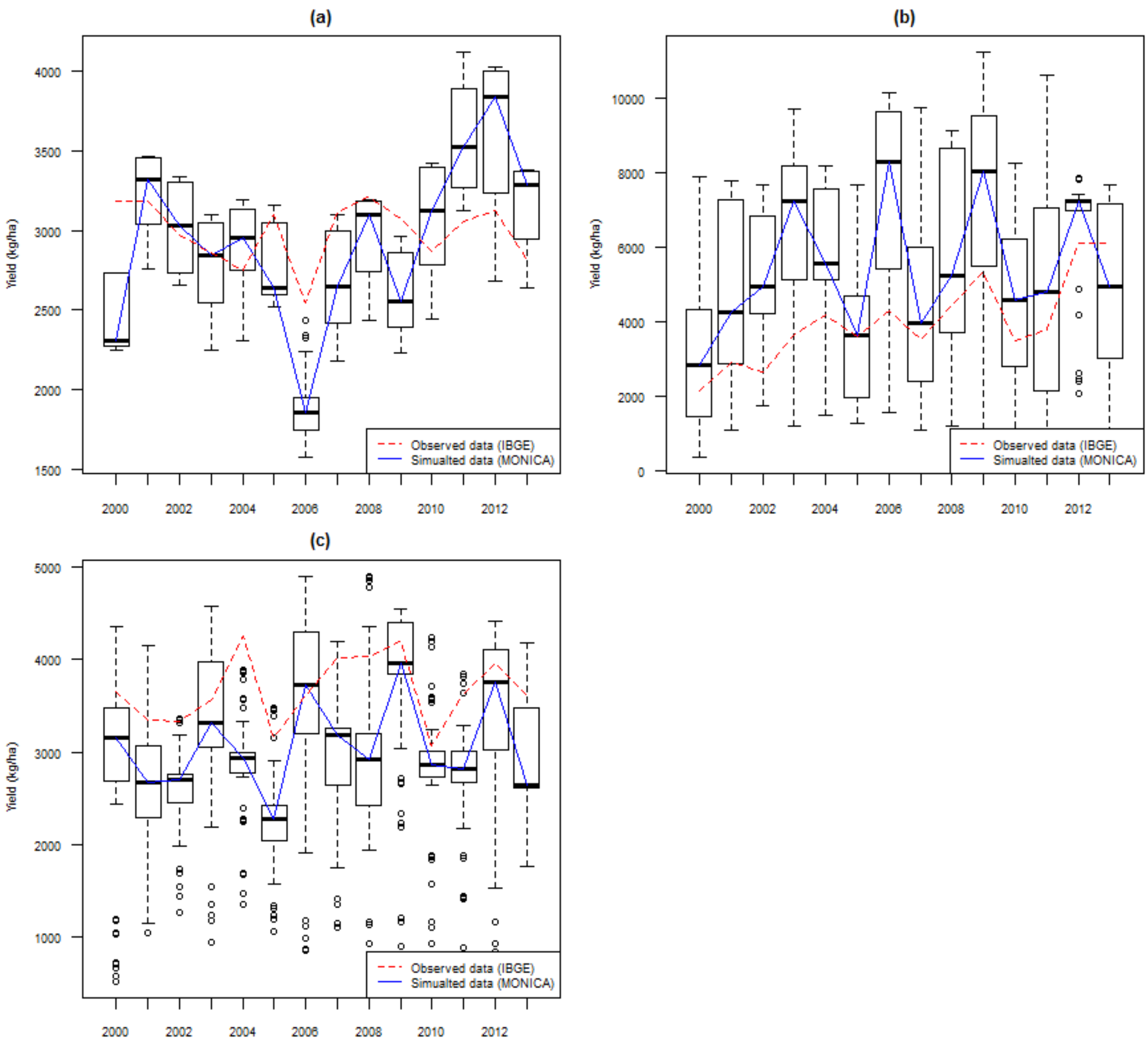

Figure 5.2. Validation of crop yields. MONICA simulation results displayed for Sapezal municipality. Figure provided by A. Hampf and the Leibniz Centre for Agricultural Landscape Research (ZALF).

5.4. Experimental set-up

Having validated our MPMAS model, we defined the baseline for our impact assessment. In this scenario reflecting current conditions, the ABC Forests and ABC Integration credit lines are available under their current conditions (described Table 5.1). We restricted the available forestry options to eucalyptus (in three production systems described in section 5.3.4) and excluded teak, since the market for this tree species in Mato Grosso is currently underdeveloped and only a very few farmers can actually access it.

In order to assess the impact of the ABC Program in Mato Grosso, we compared the results of the "*Baseline ABC*" scenario with a counterfactual scenario where no credit from the ABC Program is available. In addition to the baseline scenario with the ABC Program, we also designed scenarios with alternative implementations of ABC. In these alternative implementation scenarios, we varied the financing conditions of the ABC Program, such as the maximum amount of ABC credit that can be received by the farm, share of down payment in ABC-qualified investments, and the interest rates for ABC credits. When assessing the possible impacts of alternative set-ups, we always compared one scenario reflecting the particular set-up with our baseline. The alternative ABC implementation scenarios are as follows:

- "*Rate +1%*": In this scenario, we increase the interest rate of ABC credits by one percent per annum (to six percent). The idea of this scenario is to simulate how the reduction of interest rate subsidy (i.e. reduction of public cost of the program) impacts the adoption of the promoted agricultural systems.
- "*Own capital 50%*": Own capital requirement (i.e. down payment share) of ABC credits is reduced to 50% from the current 60% applied to iCL systems and the 65% applied to iCF, iLF and iCLF systems. With this scenario, we simulate the effect of reducing the own capital requirement on the adoption.
- "*Own capital 25%*": Same as above, but own capital requirement is reduced to 25%.
- "*Limit +1MM*": The maximum amount that can be requested by a farm agent under ABC credit lines is increased by one million BRL. Thus, in this scenario, the amounts that can be requested are three million BRL for ABC Integration and four million for ABC Forests.

In addition to the scenarios described in the previous paragraphs, we implemented a simulation scenario, where agents are allowed to choose teak growing as a farm production alternative. The results of this scenario reveal the potential impacts of the ABC Program once the teak market has been established in the study area.

All scenarios were run for three periods (three agricultural years) and capture the short- to mid-term impacts of the ABC Program. In all the scenarios, the initial areas of planted forest are set to zero, since the information on already planted forest in the study area is not available. In order to isolate the effects of the ABC Program, the scenarios were run with the constant prices and crop yields. The crop yields were set to the inter-annual averages of the MONICA simulations for 2000 – 2013. For crop prices, we used inter-annual averages for 2010 – 2013 (in 2013 real terms). The prices for agricultural inputs are estimated for 2013 from the data of IMEA (2013b). Livestock and forestry prices were estimated from the respective sources used in the parameterization of these production alternatives (sources provided in section

5.3.4). All prices for livestock and forestry were converted to 2013 real terms, as all other monetary values used in the model.

Note that in all our scenarios the land ownership of the farm agents is fixed, which means that agents are not allowed to purchase or to sell their land. Long-term rental contracts are fixed to the current contracts, no new long-term rentals can be established by the agents and the established rental contracts do not expire over the course of the simulation. However, the agents are allowed to temporarily rent out their land or sub-rent the rented land for one-year.

5.5. Results

5.5.1. ABC program and land use change

We first evaluate the agricultural land use change caused by the ABC Program, by comparing the land use in two simulation scenarios, one with ABC and one without ABC (Figure 5.3). The data was grouped into seven categories, defined as total cropland, total pasture, total area of planted forest and area of four integrated systems: (i) crop and livestock (iCL), (ii) crop and forestry (iCF), (iii) livestock and forestry (iLF) and (iv) crop, livestock and forestry (iCLF). In the total cropland, total planted forest and total pasture categories we also accounted for the land use of the respective class in integrated systems (e.g. total planted forest category besides the standalone forest plantations also includes the forest planted in integrated systems). Figure 5.3 shows that the ABC Program in its current form has significant impact on land use. Especially, the simulated areas of planted forest increase as a part of iCF and iCLF systems. In fact, there is almost no forest (only 52 hectares by one farm agent) planted in the counterfactual scenario without any policy intervention, compared to 24 thousand hectares in the baseline scenario with ABC credit. The pasture area also increases (by 30% or 16 thousand hectares) due to the adoption of iCLF systems. The expansions of the integrated systems areas are achieved at the expense of cropland, which reduces by 2% or 32 thousand hectares, and by the reduction of the unused and rented out areas. Figure 5.3 also shows that, according to our simulations, the iLF system is not adopted in either scenario, given that the integrated systems with crops are comparatively more profitable.

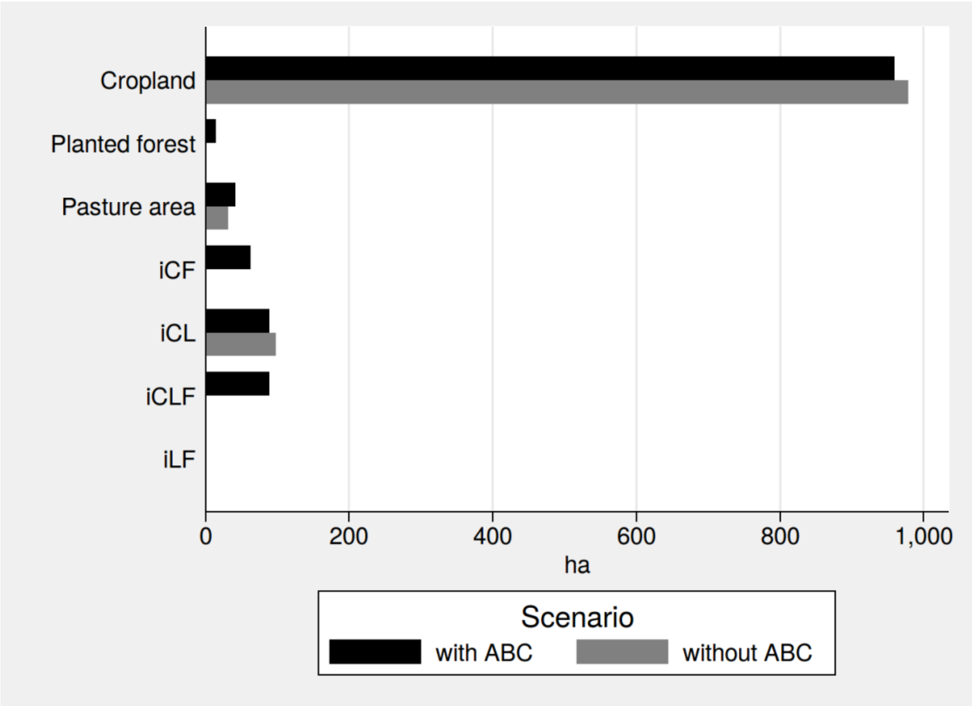

Figure 5.3. Average farm land use with and without ABC Program. MPMAS simulation results after three simulation periods (three agricultural years). Cropland, planted forest and pasture correspond to the total area of the respective land use categories, i.e. these categories include the area of the respective category in the integrated system.

As explained in section 5.4, the simulations represent five implementations of the ABC Program. We compared the results of these simulations with respect to our counterfactual scenario, in which the ABC Program is absent. For each of the five scenarios we computed the difference in simulated land use with the land use of the counterfactual scenario (Table 5.2). The changes are reported in the table for each municipality using two land use categories, total area of integrated systems and area of planted forest (including forest planted in integrated systems). As reported in the table, the large part of the area changes comes from the municipality of Sorriso, which is the largest municipality in the model both in terms of agricultural area and number of farms. The baseline implementation of ABC is simulated to increase the integrated systems area in Sorriso alone by over 200 thousand hectares and planted forest area by 21 thousand hectares. For the study area as a whole, the land use change numbers are 240 thousand for integrated systems and 24 thousand for forest. In the municipality of Campo Verde, there is an increase in area in only one of the scenarios. This is due to the presence of soils and climate conditions favorable to cotton production in that area, which yields higher per-hectare returns than integrated systems or forest plantations. In Sapezal, in certain scenarios the integrated systems may even decrease. This happens because in the scenarios with ABC lines, agents in Sapezal tend to invest in more cost-intensive iCF and iCLF systems (see for example, Figure 5.3). This significantly reduces the area of less cost-intensive iCL systems, which in some scenarios even results in negative change in the total integrated-systems area.

Table 5.2. Land use change as a result of the ABC Program. MPMAS simulation results after three simulation periods. The figures of all five scenarios above express the difference to the counterfactual scenario (i.e. absence of the ABC credit program).

Municipality	**Scenario**				
	Baseline ABC	***Rate +1%***	***Own Capital 50%***	***Own Capital 25%***	***Limit +1MM***
	Change in the area of planted forest as a result of ABC Program, ha:				
Sapezal	393	51	643	454	730
Sorriso	21 103	9 526	20 133	14 512	23 083
Campo Verde	0	0	0	845	0
Tangara da Serra	1 246	600	1 023	1 026	1 378
Canarana	1 066	792	1 036	890	1 448
Study area	**23 808**	**10 969**	**22 835**	**17 727**	**26 639**
	Change in the area of integrated systems as a result of ABC Program, ha:				
Sapezal	3 618	-3 732	-3 609	-5 963	-4 099
Sorriso	208 965	98 137	204 761	147 736	229 374
Campo Verde	0	0	0	8,450	0
Tangara da Serra	15 868	10 334	12 961	10 709	19 583
Canarana	11 617	9 686	11 790	8 556	11 984
Study area	**240 068**	**114 425**	**225 903**	**169 487**	**256 842**

According to the simulation results, increasing the interest rate of the ABC Program by 1% (compare scenarios *Baseline ABC* and *Rate +1%* in Table 5.2) leads to a reduction of the integrated systems area by 52% and to a reduction of planted forest by 54%. The reduction of the own capital requirement (compare *Baseline ABC* with *Own Capital 50%* and *Own Capital 25%*) also results in area reductions. This is because a lower capital requirement entails greater capital availability, thus enabling agents to invest in more capital-intensive and less area-intensive crop production systems. Allowing the agents to borrow one million BRL more from each of the credit lines (scenario *Limit +1MM*) leads to a positive total area change for integrated systems (+7% compared to *Baseline ABC*) and for forest plantations (+12%).

5.5.2. **Adoption of integrated systems and forest plantations**

When checking the percentage of agents adopting integrated systems with and without the ABC Program (Table 5.3), we can see that in four of the municipalities the integrated systems are being adopted in both scenarios. In the municipality of Sapezal, a significant share of agents (30.5%) adopts integrated systems even without the ABC Program. In this municipality, according to MONICA simulations, the yields of maize and soybean were lower than the study area average due to the local agro-climatic conditions, which makes agents allocate larger areas for the livestock grazing. For these agents, it is then attractive to establish iCL systems.

Table 5.3. Adoption of IS and forestry - MPMAS simulation results after three simulation periods.

Municipality	Number of agents	% of adopters		Average area of adoption, ha	
		w/ ABC	w/o ABC	w/ ABC	w/o ABC
Sapezal	82	45.1	30.5	825	803
Sorriso	426	36.4	1.6	251	5
Campo Verde	138	0	0	0	0
Tangara da Serra	53	22.6	3.8	172	22
Canarana	145	9.7	4.8	135	95
Study Area	**844**	**25.8**	**4.9**	**481**	**197**

When examining the average area of integrated systems adoption (Table 5.3), we can see that the ABC Program results in an increase of the adoption area in all municipalities where these systems are adopted in the counterfactual scenario. Through the ABC Program, the number of adopters increased by 21% and the average area of adoption by 145%. The increase is especially prominent in the municipality Sorriso, where the ABC Program serves as a tipping point, triggering the adoption. The share of adopters in the municipality rises from 2% to 36% with the activation of the ABC credits.

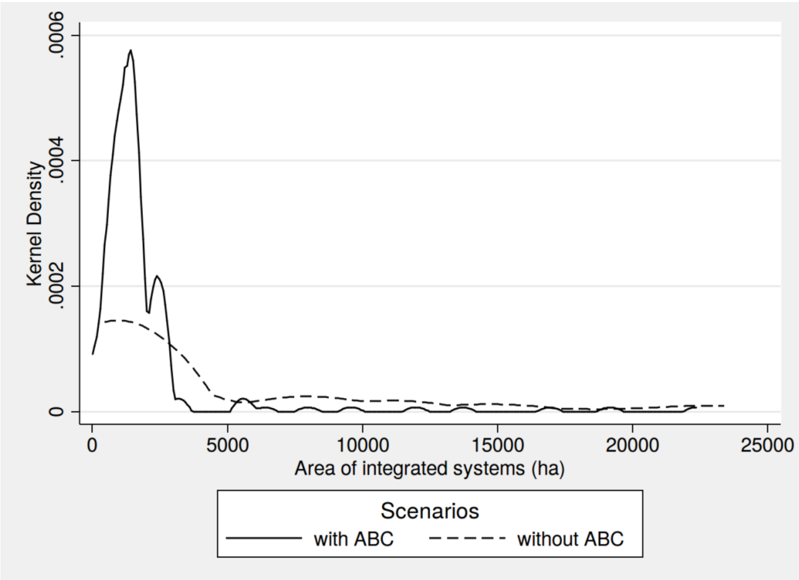

Figure 5.4. Area of adoption (by farm size) MPMAS simulation results after three simulation periods. Density functions are estimated only for adopting farms.

Density distributions in Figure 5.4 reveal that with the presence of the ABC Program more middle-size integrated systems (1,000 – 2,000 hectares) are being adopted. There are also agents who adopt large integrated systems (up to 20,000 hectares), but the share on which agents adopt the integrated systems may vary significantly. For the integrated systems including forest (iCF and iCLF) we can see in Figure 5.5 that the share of land dedicated to integrated systems decreases with farm size, while for iCL systems this is not the case. According to our results, iCL systems are the only ones that are adopted on the whole farm. The agents allocate smaller area shares to iCLF systems as they require a threefold specialization of the farm (crop, livestock and forestry). The land use share allocated with planted forests is relatively small (less than 9%) and tends to decrease with the farm size. When looking into forest systems adopted, out of three systems of eucalyptus the agents always prefer to invest into 12-year production systems with two output products (charcoal and wood). Concerning livestock, the most popular system is the intensive fattening system with sown brachiaria grassland pasture. The introduction of the ABC Program does not change the choice of livestock system, despite the reduction in the livestock area. The intensive fattening system with sown brachiaria grassland pasture remains the choice of all the agents who choose pasture.

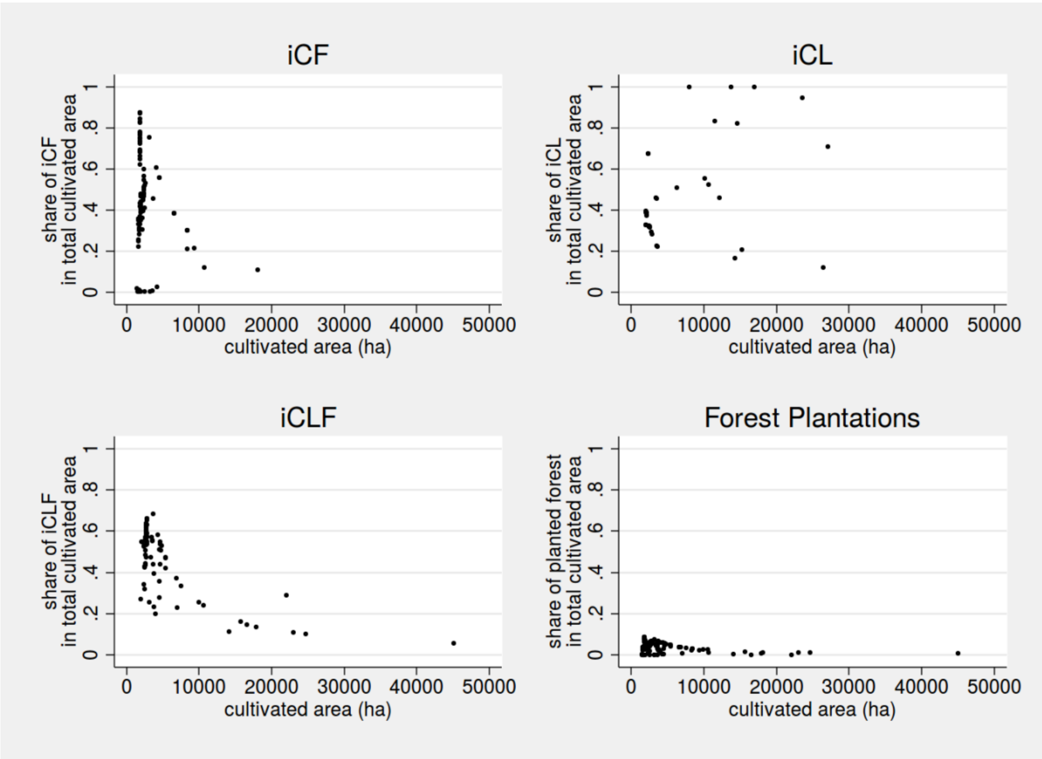

Figure 5.5. Area of adoption (by system) in the baseline scenario with ABC ProgramMPMAS simulation results after three simulation periods.Scatter plot for forest also considers forest grown as part of integrated systems.

5.5.3. **Costs of ABC integration and ABC forests credit lines**

In Table 5.2 we have already computed the effects of the ABC Program in terms of the land use change. As a next step, we divided the simulated costs of the two components of the ABC Program implemented in our model (ABC Forests and ABC Integration) by the land use changes from Table 5.2. The resulted per hectare costs (provided in Table 5.4) indicate how much of government spending for ABC credit is required to increase the promoted low-carbon land uses (integrated systems and planted forest) by one hectare on average. In this estimation, as costs of the ABC Program we considered only the cost of subsidizing the interest rates, while the associated transaction costs were neglected.

Table 5.4. Budgetary costs of ABC Forest and ABC Integration with respect to promoted land use. MPMAS simulation results after three simulation periods. The figures of all five scenarios above express the difference to the counterfactual scenario (i.e. absence of the ABC credit program).

Municipality	Scenario				
	Baseline ABC	***Rate +1%***	***Own Capital 50%***	***Own Capital 25%***	***Limit +1MM***
	ABC Forests. Costs per additional ha of planted forest, BRL/ha/year:				
Sapezal	14.7	6.9	21.1	32.1	14.7
Sorriso	14.6	10.4	20.8	31.3	14.6
Campo Verde	N/A*	N/A*	N/A*	31.4	N/A*
Tangara da Serra	14.6	10.5	20.9	31.2	14.6
Canarana	15.4	10.8	22	33.2	15.2
Study area	**14.6**	**10.4**	**20.9**	**31.4**	**14.6**
	ABC Integration. Costs per additional ha of integrated system, BRL/ha/year:				
Sapezal	472.6	(**)	(**)	(**)	(**)
Sorriso	9.3	9	21.1	54.3	9.4
Campo Verde	N/A*	N/A*	N/A*	46.4	N/A*
Tangara da Serra	18.5	17.3	34.9	65.6	16.9
Canarana	42.1	24.6	55	98.6	53.6
Study area	**18.8**	**19.1**	**32.8**	**71.1**	**21.2**

Per hectare cost values from Table 5.4 indicate that, at the study area level, for the ABC Forests credit line, the most cost-efficient of the five scenarios is the scenario *Rate +1%*. In the case of the ABC Integration, *Baseline ABC* and *Rate +1%* scenarios, both have similar low costs at the study area level. When comparing the simulated per hectare costs across different municipalities, it can be seen that for ABC Forests the costs are similar between the municipalities in one scenario. The situation is different for the costs of ABC Integration. This is because, unlike the forestry plantations, where according to our simulations, the 12-year production system for eucalyptus is clearly the best production alternative, for iCL and iCLF systems there is no dominant choice of the crop production practice. Here, the agents choose a wide range of different practices, based on their resource endowments and environmental conditions. Interestingly, in Sapezal municipality the cost effectiveness of the ABC Integration program is very low because of the area reduction, as explained earlier.

5.5.4. **Effect of teak market access**

All the results presented in the above sections correspond to the simulations, in which teak production has been switched off. We now review the simulated impact of establishing output markets for teak production (i.e. enabling the marketing of teak wood). Table 5.5 compares the simulation results of the *Baseline ABC* scenario with teak production deactivated with another version of the *Baseline ABC* scenario, in which we switched on the teak production alternatives. The table shows that with the introduction of teak, the number of adopters increases in each of the four municipalities where teak is grown. In total, the number of adopters increases by 21% compared to the scenario with no teak, resulting in 31% of all farms adopting the integrated and forestry systems. The average area of the planted forest per adopter increases notably from 28.3 (in the scenario without teak) to 48.7 (in the scenario with teak) hectares, which is a 72% increase. According to our simulations, teak is a more profitable forestry system than eucalyptus and its introduction in the simulation scenario results in more forests planted at the study area level. At the municipality level the area increase of the planted forest happens in the municipalities of Sapezal, Tangara da Serra and Canarana, while in Sorriso the area decreases slightly. In Sapezal, the area of forest per adopter increases tremendously, from 4.8 to 211.1 hectares. The different model responses in different municipalities are caused by the implemented inter-regional differences in agro-climatic, structural and market conditions. These differences influence the profitability of the land use activities in the model and lead to the diversity in results.

Table 5.5. Effect of access to the teak timber market. MPMAS simulation results after three simulation periods.

Municipality	% of adopters		Average area of planted forest, ha/adopter		Cost of added forest, BRL / ha /year	
	w/o teak	w/ teak	w/o teak	w/ teak	w/o teak	w/ teak
Sapezal	45.1	52.4	4.8	211.1	14.7	19.4
Sorriso	36.4	44.4	49.5	47.3	14.6	19.7
Campo Verde	0	0	N/A	N/A	N/A	N/A
Tangara da Serra	22.6	24.5	23.5	32.4	14.6	20.1
Canarana	9.7	13.1	7.7	12.9	15.4	20.8
Study Area	25.8	31.3	28.3	48.7	14.6	19.6

* - not applicable (N/A), when there is no adoption of forest.

Along the increase of the forest area in the scenario with teak, costs of the ABC Forest Program (in per hectare of added forest calculation), however, also increase. In the scenario without teak, they constitute around 15 BRL per hectare per annum, while in the scenario with teak, they are around 20 BRL per hectare per annum. In the study area as a whole, the costs increase by 34%. The reason for this increase is the higher investment costs of the teak plantations compared to the eucalyptus ones. In the scenario with teak, the agents take larger amounts of credit from the ABC Forests program, which leads to the cost increase both in absolute and per hectare terms.

5.6. Discussion and conclusions

5.6.1. Implementation of preferential credit programs

The results of our simulations suggest that ABC Integration and ABC Forests credit lines of the ABC Program have the potential to promote the adoption of integrated systems and forest plantations in Mato Grosso. The impact of the ABC Program may be improved by increasing the limits that farmers are allowed to borrow under these credit lines. In this case (reflected in the assessment by *Limit +1MM* scenario), our bioeconomic simulations suggest a considerable increase of 7% in the area of adoption. However, the simulated per hectare costs in this case also increased by 13%. This implies that, if the policy goal is to increase total area under integrated systems and forest plantations, larger amounts of credit have to be provided. Especially for large farm holdings (i.e. “thousand hectares plus”) that operate the majority of agricultural land in Mato Grosso (IBGE, 2006), the current limits appear to be too low.

The most efficient scenario in terms of per hectare costs of the program is the scenario Rate +1%, though in this scenario the area of adoption is the smallest (see Table 5.3 and Table 5.4). This result suggests that the reduction of the interest rate subsidy may lead to subsequent discontinuity of technology adoption. Therefore, in order to sustain the effects of the program, the government should provide financing in the long-run.

According to our simulations, the decrease in own-capital requirement (scenarios *Own capital 50%* and *Own capital 25%*) may lead to lower adoption rates due to the higher amount of capital available for competing crop-based land uses. Based on these simulation results, it is possible to conclude that the current financing share is appropriate given the ABC Program’s goals.

5.6.2. Interregional differences of the impacts

Our simulation results suggest that the impacts and cost-effectiveness of the ABC credit lines vary significantly across the regions in our study area, given the different opportunity costs of the agricultural land. Given such heterogeneity, it might be ineffective to apply identical conditions of the ABC Program in the entire country. Tailoring financing conditions to smaller geographical units of the country could be achieved, for example, by using IBGE's subdivision of "mesoregions" for location-specific ABC Program implementations.

5.6.3. High-value timber as an investment opportunity

The results of our simulations indicate that the farmers' ability to access the teak market may have a significant influence on the planted forest area at the farm level. Hence, enabling more farmers in Mato Grosso to market teak timber would increase the impacts of the ABC Program in terms of area. Once the teak market has been made accessible in our simulations, more model agents adopted forestry systems. However, diffusion of teak plantations in Mato Grosso would also translate into significantly higher costs for the ABC Integration credit line, when calculated per hectare of planted forest. If the policy goal is to increase the area of the planted forest in the state, improving the teak market structure can be a promising strategy for future regional development. 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.

5.6.4. Relevance of bureaucratic and knowledge constraints

Credit from the ABC Program has not been regarded as a crucial determinant of the adoption of integrated systems in Mato Grosso so far. In fact, a small share of current integrated systems adopters have used ABC credit lines (Gil et al., 2015). However, our simulation results indicate that the ABC credit program has the potential to prompt a large-scale adoption of integrated systems and highlight the importance of understanding and eradicating the causes of this discrepancy. Mato Grosso's farmers interviewed by Gil et al. (2015) named bureaucracy as a major factor constraining the usage of the ABC credit lines. Such burden is reflected by excessive documentation requirements of the ABC Program, strict environmental conditions of project implementation and high rates of rejection of credit applications. We expect that relaxing the over-demanding and difficult-to-comply requirements will increase the actual impact of the credit lines.

Another important practical constraint preventing farmers from adopting forestry and integrated systems is the lack of know-how required for the implementation of these production systems (Gil et al., 2015). The empirical findings on agro-ecological innovations (Caviglia & Kahn, 2001; Uphoff, 2002; Knowler & Bradshaw, 2007; Wollni & Brümmer, 2012) suggest that the adoption of sustainable agricultural practices (including the ones promoted by the ABC Program) in Mato Grosso would require effective technical support to potential adopters provided by local extension service. Other mechanisms to improve knowledge and capacity building – such as linking farmers with applied research, outreach programs and social learning through farmer organizations – are also likely to positively affect the adoption (Lee, 2005).

5.6.5. Model limitations and future research avenues

As discussed in the previous section, the transaction and learning costs associated with establishing new agricultural practices and technologies on-farm influence farmers' decisions to take this step. Together with the economic benefits of the innovation and externally provided economic incentives, these barriers constitute the factors defining the actual diffusion of agricultural innovations (Lee, 2005). Our present model application includes the innovation benefits and the additional incentives (ABC Program), but does not account for the bureaucratic and social barriers to adoption. Therefore, the simulation results should be interpreted as an ideal technical change situation, showing the potential adoption once these barriers have been removed. It is possible to include these barriers into agent-based simulation following the approach of Schreinemachers & Berger (2011) and enable the model to predict the actual adoption patterns – which will be done once the required empirical data is available. Also the study of Gil et al. (2015) suggests that further research on administrative, social and information constraints to adoption in Mato Grosso is needed.

The absence of consistent experimental evidence on the agricultural performance of integrated systems in the *Cerrado* and *Amazon* biomes, especially regarding the likely interaction effects, led to simplifications in our economic assessment. Full understanding of the economic costs and benefits of the integrated systems is certainly conditioned to the availability of data on the long-term productivity of crops, livestock and forest plantations in integrated systems. Research centers in Brazil have to address this knowledge gap by conducting long-term experiments and making their results available to the public.

The parameterization of our simulation model relied on 12 farm profiles from five municipalities (IMEA, 2013b), which is the best publicly available farm-level dataset that includes production costs. Given the size of Mato Grosso, which has 141 municipalities and includes over hundred thousand farms (IBGE, 2006), a larger sample of farm production cost data is needed. Making more detailed farm-level data available for research will greatly improve the understanding of the agricultural systems and transformation processes in Mato Grosso. This is especially important given the global environmental and economic significance of the state of Mato Grosso.

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6. Discussion and conclusions

The previous chapters showed four different studies related to land use change and the adoption of two major agricultural intensification pathways in Mato Grosso, Brazil – namely pasture to crop conversion (P2C) and integrated systems (IS). Chapter 2 looked at cropland expansion on degraded pastures, how local land markets function, and their importance for land transactions and P2C occurrence. Chapter 3 examined the adoption of IS from a household perspective by mapping and describing IS technical and non-technical features, making links between farmers' and ranchers' profiles and the choices of each group concerning the transition from specialized to integrated farming. Chapter 4 built on chapter 3 to investigate the broader dissemination of the most common type of IS in Mato Grosso, integrated crop-livestock systems (iCL), through a cross-sectional analysis of household and regional variables. Finally, Chapter 5 presented an assessment of the influence of credit provision on the adoption of IS and planted forests within the framework of the ABC Plan under different scenarios.

Together, these chapters constitute a first attempt to look into two recent, yet transformative processes of agricultural intensification. To the best of our knowledge, no prior study had ever looked into two concomitant intensification pathways in the same study region. Specifically concerning P2C and IS, most of the existing literature is limited to their environmental impacts and/or focus on case studies of limited generalizability. This thesis bridges these gaps by offering empirical evidence of socioeconomic costs and benefits of IS and P2C at the state level, how these processes work in practice and how farmers perceive them. Besides acknowledging the richness and complexity of these land use change processes, this approach generates information that help inform and validate descriptive and predictive models of land use change in Central Brazil. Moreover, the relevance of Mato Grosso as a case study relies not only on its crucial role in protecting the Amazon rainforest but also on its diversity. Although intensification processes are context specific, the various agroclimatic conditions, groups of stakeholders and land use trajectories found within the state offer insights into similar processes elsewhere.

Existing studies on land use change in Brazil usually rely on a single research method and therefore overlook important aspects of such change. Although the analysis of spatial patterns at a more aggregate level is important to reveal the influence of regional factors on land use, it does not capture the human dimension of land use choices. Likewise, traditional agricultural development theories exclusively focused on land attributes such as soil suitability might explain some of the elements involved in farmers' land use choices in Mato Grosso but fail to capture micro-level factors and unobservables which are increasingly important with regards to land use decisions. By combining multiple research methods, this thesis shed light on those factors as well as generated information on the comprehensiveness and location of P2C and IS, how each of these strategies has been operating in practice and the challenges associated to their dissemination. The qualitative and quantitative methods used here are complementary, as described by O'Neill et al. (2013, pp. 448): "*Qualitative research methods are generally employed to explain outcomes, make causal inferences, identify causal mechanisms, or identify historical processes within a single or a small set of cases. Quantitative methods, on the other hand, usually employ statistical techniques to map relationships, assess correlations, and/or make descriptive and causal inferences by analyzing large sets of data*".

The following sections further explore the significance of these findings in a holistic manner, drawing inferences on different dimensions of agricultural intensification in Mato Grosso. Going beyond what has already been presented in chapters 2, 3, 4 and 5, they bring together complementary literature to examine broader socioeconomic and environmental implications of intensification through P2C and IS. At the end, some policy recommendations are outlined, as well as the applicability of the results, their limitations and future research avenues.

6.1. Agricultural intensification is not a single process

Our findings corroborate the assumption that agricultural intensification is not a single process. By looking into the specifics of P2C and IS, we showed that each intensification strategy is associated to a particular agricultural development trajectory with unique impacts. The factors on which these impacts depend include the characteristics of the place where it happens (e.g. the actors involved directly or indirectly, institutions, land attributes, whether the region is on the agricultural frontier or near well-established agricultural centers, etc.); existing macro-economic conditions (e.g. policies, institutions and market dynamics); the drivers of the process (e.g. market changes, specific policies imposed by the government, or others); how inclusive it is (whether it primarily involves large farmers, smallholders or both); and the characteristics of the technology (or technologies) through which intensification occurs.

Several nuances and site-specificities of land use change and agricultural intensification in Mato Grosso have been revealed. These include the relevance of farmers' cultural background for technology adoption decisions, the different risk profiles of farmers versus ranchers, how several land market institutions are applied, and some non-productive utility sources that influence the value attached to a land use. The low presence of trees and the intensive management practices that characterize IS in Mato Grosso support the conclusion that certain intensification strategies like conventional agroforestry systems may be dissonant with the reality of large, highly intensified agricultural enterprises in Mato Grosso. Although in that sense both IS and P2C may seem more realistic options for the intensification of agricultural production in the state, the parallels and differences that exist between the two might lead to very different outcomes and must be carefully assessed by policy makers.

6.1.1. **Parallels between P2C and IS**

If we assume that integration may happen at multiple spatial and temporal scales, possibly involving more than one farmer (Adger et al., 2005; Bungenstab & Amleida, 2014; Thornton & Herrero, 2015), we might conclude that there is some overlap between certain categories of P2C and certain categories of IS. From the perspective of time, the transition from pasture to crop and then back to pasture which characterizes P2C rental contracts is comparable to integrated crop-livestock systems (which, according to the definition used in this thesis, consist of rotating crop and pasture periodically in the same area). The only difference is the frequency of rotation and, consequently, its impacts on soil fertility and productivity. From the perspective of space, integration could happen at the farm or landscape level, and the rotation of crop and pasture could take place across farms provided that farmers and ranchers agree to participate in a collective arrangement.

The decision to engage in P2C and the decision to engage in IS are each a function of individual factors as well as economic, institutional and policy conditions at the aggregate level. Individual factors include households' time preferences, risk perception, know-how, and investment capacity. On the other hand, the functioning of land markets, regional supply chain infrastructure and macroeconomic conditions are some of the variables that may constitute a more or less favorable context for intensification. The relative importance of each of these factors varies across P2C and IS given the peculiarities and trade-offs that each of them entails.

Given the poor management practices that characterize most of the ranching activities in Mato Grosso, including low level of inputs and lack of conservation measures (Silva et al., 2004; Fearnside et al., 2009; Batlle-Bayer et al., 2010; Carvalho et al., 2010), both P2C and IS may contribute to increase food production while rehabilitating degraded pastures. P2C through rental contracts is a way of keeping the land and still benefiting from this market dynamics in Mato Grosso. IS are also attractive in that sense, since it offers an opportunity for ranchers to continue in the sector by rehabilitating their pastures and ultimately becoming more competitive.

Another parallel between P2C and IS is that both involve high implementation costs, including expenses related to land conversion, infrastructure adjustments and managerial changes. Theories of technology adoption tend to look at agricultural innovations and their diffusion process as a fixed/limited choice between different activities. However, as chapters 2 and 3 have shown, IS and P2C are technically flexible technologies that do not have to be adopted in the entire farm at once and whose adoption may be easily reversed provided that ISs do not involve trees of long life cycles. From a cost perspective though, the reversibility of P2C and IS tends to be limited by high costs associated with machinery purchase, construction of roads and silos, irrigation, etc. Contrary to intensification strategies that require only small adjustments in conventional farming systems and may be relatively inexpensive, such as high yielding seed varieties or paddocks, P2C and IS are two transformative technologies whose adoption involves more complex, systemic and often costly changes.

6.1.2. Contrasts between P2C and IS

The contrasts between P2C and IS are manifold and concern advantages and disadvantages of each strategy as well as motivations for their adoption. As mentioned in section 2.1., factors influencing access to markets and information are important for P2C but even more so for IS given the higher complexity of the latter. The finding presented in chapter 4 that the presence of soy and pastures is not a condition for (nor a good predictor of) the occurrence of iCL confirms the uniqueness of IS.

Even though IS and P2C may contribute to restore degraded pastures, that alone may not ensure increased environmental quality or resilience in the long-run. The conversion of pastures into cropland establishes a monoculture, while IS entails greater diversification of species, regular rotation of grasses and crops and, hence, greater environmental benefits. In fact, even after the pasture has been recovered and brought back into cultivation, soil fertility will not sustain itself for the same time under a regime of monoculture (P2C) and periodic rotation of species (IS) – bringing us to the conclusion that P2C is more reliant on fertilizers. Although we could not compare how much fertilizer was needed for soybean cultivation in monoculture versus integrated systems, the findings in chapter 2 offered evidence that the second optimizes the use of resources and tends to be generally less reliant on external inputs (e.g. crop generates fodder for the animals, fertilizer residuals benefit the pasture, land is used for a longer period of time, etc.). More details on the comparison between P2C and IS in terms of their environmental impacts are provided in the following sections.

Crop farming ensures the generation of economic returns in the short run for both IS and P2C, however the former has a different cash flow and possibly shows a longer payback period due to the longer maturity cycle of cattle and forest plantations. The discrepancies between P2C and IS with regards to cash flow, level of complexity, labor intensity and short- versus long-term resilience explain why, within the group of medium-large producers investing in intensification in Mato Grosso, it is possible to find households with distinct profiles and/or motivations. While IS adopters opt for production diversity and are mostly long-term oriented, ranchers who engage in P2C are usually interested in immediate gains from farming (in the case of self-conversion) or land renting.

According to the conceptualization proposed by Byerlee et al. (2014), at least from a theoretical point of view, P2C conversion could be considered a market-driven intensification process since it results from a shift in the product mix to higher value crops (soybean) due to new market opportunities. The adoption of IS, on the other hand, could be considered a technology-driven process which occurs when technical changes in farming (such as the rotation of different species) allows more output per unit of land for the same level of inputs over the long run. Although ranchers engaging in P2C through self-conversion are probably more open to innovations than others, it would be wrong to assume that they would be more prone to adopt IS afterwards as the driving forces behind farmers' decisions to engage in each of them are different.

6.1.3. Broader impacts of the wide-scale adoption of P2C vs. IS

Even though P2C and IS are often treated indistinctly under the concept of agricultural intensification, our results reveal that each of these strategies has its own advantages and disadvantages and that their wide-scale dissemination may lead to different individual and societal impacts. This includes the risk of further deforestation, the potential to mitigate climate change, the provision of environmental services and the impacts on livelihoods.

Land sparing vs. deforestation

As mentioned in Chapter 3, the Brazilian Federal Government claims that P2C and IS may help mitigate GHG emissions in the agricultural sector by reducing the life cycle of cattle, creating carbon sinks (especially using forest plantations in the case of some IS) and avoiding deforestation due to agricultural expansion. Furthermore, the government expects these outcomes to deliver 10-90% of the GHG mitigation target defined under the National Climate Action Plan (Cohn et al., 2011). The mitigation potential of the first two points is consensual among scientists, but the third point (related to land sparing) has led to a great deal of discussion, as outlined in the introduction of this thesis.

Much of the recent debate was based on the understanding that intensification has a forest-saving effect in contexts where agricultural expansion is a result of increasing agricultural profitability; alternatively, a forest-clearing effect when agricultural expansion is a result of population growth, low agricultural productivity, and poor technology (Kaimowitz and Angelsen, 1998). Making a parallel with the agricultural context of Mato Grosso, an open economy closely connected to the international market through exports, our results offer evidence that agricultural expansion is mostly a result of the increasing profitability of agriculture due to rising commodity prices and technical advancements. However, in frontier regions within the state, agriculture may still be an option in response to population growth, just like it has been reported in other deforested regions of the world going through analogous processes (Walker et al., 2002; Maertens et al., 2006). Apart from this discussion, it has been established that improved productivity cannot guarantee land sparing and often enhances the attractiveness of a particular area for agricultural production (Angelson & Kaimowitz, 2008; Meyfroid et al., 2010; Lambin & Meyfroid, 2011) but, nevertheless, it is a necessary complement to more direct conservation policies if agricultural output is to increase at the national scale (Godfray at al., 2010; Tilman et al., 2012).

In order to avoid further deforestation as a result of intensification, it is important to ensure that intensification and anti-deforestation policies are coordinated, so that the risk of leakage is reduced and intensification results in land sparing (Rudel et al., 2009; Angelsen, 2010). Whether or not agricultural intensification through P2C and IS helps ensure the world's growing food demand while reducing the pressure on forests at the state level ultimately depends on policy coordination and enforcement. Also, although both P2C and IS may ensure more food per hectare than current land uses in Mato Grosso do, IS ensures the provision of a more diverse basket of agricultural goods (such as timber, milk, fodder, etc.).

Climate change mitigation

It is already possible to see how agriculture in Mato Grosso affects and is affected by climate change. Conversion of natural vegetation and pastures to row-crop agriculture accounted for a large share of the state's total GHG emissions (179TgCO2-eq/yr from 2001 to 2006) (Galford et al., 2010). At the same time, rising temperatures and unstable rainfall patterns are expected to cause a shift in areas currently suitable for certain cultivars and double cropping (Assad & Pinto, 2008). Higher returns per unit of land achieved through P2C or IS may lead to an increase in total food production and consequently in the overall GHG emissions associated to food processing, transportation and energy consumption. Yet, P2C and IS also lead to the decrease of on-farm GHG emissions generated to produce one unit of food.

According to the Brazilian GHG Inventory, major sources of GHG emissions related to beef cattle include nitrous oxide (N_2O) from application of manure, nitrogen (N) in manure applied for fertilization or directly disposed on pastures, and methane (CH_4) from enteric fermentation and manure. Major sources of GHG emissions related to soy are N_2O from soils (including maize in the case of double cropping and fertilizers), synthetic fertilizers applied to soils, and N that returns to the soils as agricultural residues. The atmospheric deposition of volatilized N and N lost through leaching and runoff might be present in soy and cattle systems, but data on that is unavailable (Government of Brazil, 2004).

In cases where P2C represents a permanent shift from degraded pasture to soy monoculture, it may extinguish GHG emissions associated to degraded pastures (Smith et al., 2008; Gerber et al., 2013). However, P2C will also lead to emissions associated to the monoculture of soy such as more applications of fertilizers, higher use of fuel in intense field operations, decomposition of crop residues, among other practices typically employed in conventional soybean monoculture in Brazil (Castanheira & Freire, 2013; Raucci et al., 2015).

IS, on the other hand, represents the shift from a specialized to a diversified system. Climate adaptation goals and the most efficient ways to achieve them are context-specific and thus might differ across different regions within Mato Grosso. Yet, it is clear that IS are able to increase resilience and reduce vulnerability to climate change through a number of ways. These include increased land quality (higher land productivity and its maintenance over time at relatively low costs), higher income generation (it is cheaper to produce beef in integrated systems since cattle will be ready for slaughter earlier, the rotation of species might help restablish soil fertility naturally, etc.) and finally diversification of production (which might bring additional income streams and flexibility to deal with market fluctuations affecting input costs and/or prices of products) (Carvalho et al., 2014).

Table 6.1 summarizes major GHG sources in a stylized way and shows how the shift from current land uses (specifically soy monoculture and degraded pasture) to IS is likely to impact overall GHG emissions in Mato Grosso. It should be noted that some of the sources are not necessarily related to soybean itself but the way it is cultivated (e.g. N losses from leaching and runoff can be significantly reduced as long as soybean fields are well-managed) (Raucci et al., 2015). Likewise, pastures might act as a carbon source or a carbon sink depending on the way they are managed and whether the potential sequestration of deep-rooted grasses is accounted for (Fisher et al., 1994; Fearnside & Barbosa, 1998; Bustamante et al., 2012).

Table 6.1 - Potential GHG mitigation through the shift from soy monoculture and degraded pasture to integrated systems.

	Characteristics of IS	Soy Monoculture to IS	Degraded Pasture to IS
Direct Emission Reduction	Reduced inputs	• Low fertilizer use and reduced leaching • Fewer herbicide use • Lower diesel use for field operations	
	Accumulation of organic matter	• Soil may act as a C-sink	• Soil may act as a c-sink
	Growth of trees	• Trees may act as a C-sink	• Trees may act as a c-sink
	Improved livestock cycles		• Reduced enteric fermentation and manure due to shorter livestock cycles
Indirect Emission reduction	Supply Chain Emissions	• Lower fertilizer production emissions • Reduced deforestation due to on-site coal production for grain drying	
	Land Sparing	• Increased yields	• Increased yields
			• Less feed production for supplementation

As explained in chapter 3, the calculation of exact carbon accumulation rates in the soil requires measured data and sophisticated soil analyses which were beyond the scope of this thesis. Nonetheless, our results clearly suggest the occurrence of carbon accumulation based on data reported by farmers with respect to field operations and increases in productivity. As reported in section 3.3.6 and corroborated by Assmann et al. (2014), IS are often associated with low-carbon conservation practices such as minimum-tillage. Most importantly, instead of grazing for about 3.5-4 years as in conventional livestock production systems, some IS adopters reported that their cattle reached slaughter weight after 2.5-3 years on average. Furthermore, shorter cattle life cycle contributes to minimizing methane emissions and mitigating climate change.

These findings are aligned with a growing body of literature (Carvalho et al., 2014; Salton et al., 2014) which has already shown that ISs have the potential to mitigate the amount of GHG emissions in the agriculture by reducing the life cycle of the animals (which usually lose weight during the dry season and thus take longer to be ready for slaughter); increasing tree plantations; increasing organic matter in the soil; reducing the amount of inputs; and reducing the use of diesel in field operations.

An important point to consider though is that IS' potential to reduce GHG emissions in agriculture will not be fully realized if the participation of forestry remains low and if other aspects of IS (e.g. rotation frequency, mix of species, management practices) do not follow minimum requirements.

Besides these aspects, the rate of carbon accumulation and the consequent increase in biomass and productivity depend on soil properties and the field operations conducted. As revealed here, farmers tend to implement IS in different ways; the rotation frequency between crop and pasture ranges from 2 to 5 years and may change in the future according to farmers' preferences and possibilities. Besides, most of the identified IS are younger than two and a half years and have not reached stability in terms of microbiotic activity and organic matter increment. These factors make it hard to calculate an average rate of carbon accumulation in the soil (Sanderman & Baldock, 2010; Franzluebbers et al., 2014).

Other environmental impacts

Through the cultivation of different crop and grass species and their periodic rotation in the same area, IS will almost definitely ensure greater environmental gains over the long-run than those associated to crop monoculture established through P2C. It is widely known that IS leads to better nutrient cycling, improves the physical, chemical and biological characteristics of the soil due to an increase of the organic matter contents, increases soil resilience during dry-spells, minimizes the occurrence of pest and weeds, improves animal well-being thanks to the thermal control provided by the shade of the tress, facilitates water recharge, improves air and water quality, contributes to the landscape restoration and promotes species conservation (particularly concerning the soil microbiology) (Jose, 2009; Balbino et al., 2011; Lemaire et al., 2014; Salton et al., 2014).

Socioeconomic impacts

Our findings on P2C and IS indicate the existence of notable differences between these two intensification strategies with respect to their potential socioeconomic impacts. Concerning land concentration, as highlighted throughout this thesis, beef cattle production in Mato Grosso is mostly free-range and extensive, while cattle properties are usually large, unproductive and poorly managed. The large size of the ranches is actually what allows this low input-low output model of production to sustain itself despite their low productivity. The trend observed in Mato Grosso is that land owned by unproductive ranchers is rapidly being reallocated to higher-value activities, particularly soy farming. Moreover, the consequent rise in land prices (especially where logistics are favorable for the production of grains) reinforces this trend. In this context, P2C may have different impacts on land concentration depending on the stakeholders involved in it as well as the P2C mechanism in question.

Concerning land concentration at the regional level, the results in chapter 2 suggest that some types of P2C may aggravate it while others may prevent it. For instance, P2C through self-conversion or rental contracts would not affect land ownership in the long-run thanks to their temporary nature, but could provide an opportunity for small and medium producers (both ranchers and farmers) to obtain higher levels of income and remain in the business. Pasture conversion through selling, however, represents a permanent change in land ownership, and its impacts would vary depending on who acquires the land. Permanent P2C conducted by large investment groups may lead to two effects, the first being the increase in their share of total land and the second being the increase in competitiveness (which could eventually drive small soy producers out of business). Permanent P2C conducted by smaller soy farmers, on the other hand, would lead to effects similar to those arising from temporary P2C. Given these considerations and our results on P2C being conducted by large investment groups in Northeastern Mato Grosso, land concentration caused by permanent P2C could become more pronounced in other marginal areas of the state as well.

IS, on the other hand, might not have the same effect on the land ownership structure. Although modeling results presented in Chapter 5 showed that integration may be adopted in large properties, what they highlight is the potential for IS adoption (without establishing causality links between land concentration and IS diffusion). Also, IS could allow undercapitalized ranchers and farmers to increase their competitiveness and remain in the business. That could offset at least part of the land concentration effect that may result from some of the P2C contracts discussed above. The possibility that IS becomes highly profitable and IS adopters start expanding their production area by acquiring other farms should be investigated in the future. Given that IS has been adopted in such a small share of Mato Grosso so far, its impacts on land concentration are not that significant.

From the perspective of income generation, the expansion of P2C might generate more capital in the short run than IS thanks to the higher profitability of soy as compared to cattle. However, P2C might also increase risk as monoculture is more vulnerable to market fluctuations, climate stresses and pest outbreaks (Lin, 2011; Sulc & Franzluebbers, 2014; Lemaire et al., 2015), while IS would allow producers greater flexibility to switch to an activity both in terms of technical know-how and machinery. Finally, it should be noted that P2C and IS involve mostly medium and large producers in Mato Grosso, suggesting that incentives for the participation of smallholders in these agricultural intensification processes must be put in place.

Related to income concentration is the generation and maintenance of jobs. As pointed out by Cohn (2011), "incomplete labor markets or shortage of labor supply (particularly in remote regions) may make producers more likely to choose relatively more land- or capital-intensive types of production." Along the same lines, Lee (2005) discusses input substitutability and labor, highlighting that the opportunity costs of labor and the role of labor contracting influence farmers' decisions to adopt a system. Considering that degraded pastures have very low productivity and employ very few people, their conversion into cropland through P2C might require more labor despite the fact that large-scale soybean production in Mato Grosso is highly mechanized (Roessing & Lazzarotto, 2004). Concerning the impacts of IS on job generation, some studies have indicated that agroforestry practices do not always increase labor demands, may reduce seasonal labor peaks and may increase returns to labor (Hoekstra, 1987; Place et al., 2002; Bosma et al., 2010). The results on labor demands for iCL systems were inconclusive as for the degree to which that applies to the types of IS found in Mato Grosso and the consequent relevance of labor availability for IS adoption. Still, the limited availability of labor – particularly skilled labor – is often considered by farmers an obstacle to IS adoption (particularly when forestry activities are involved, as revealed in chapter 3). This suggests that intensification through IS is prone to generating more jobs compared to P2C.

Irrespective of slight differences, it is worth noting that iCL systems and P2C are much closer to conventional farms in terms of low labor-intensity and high output levels per unit of land than other kinds of mixed systems such as conventional agroforestry. This makes iCL and P2C realistic alternatives in a state like Mato Grosso, where large-scale commercial agriculture is already in place.

6.2. Policy recommendations for agricultural intensification

Both P2C and IS have positive and negative impacts. Although they represent an improvement relative to the *status quo* for bringing degraded lands back into cultivation and possibly reducing overall input requirements for each unit of food produced, neither can be considered a perfectly sustainable intensification pathway (Tscharntkea et al., 2012; Peterson & Snapp, 2015). Still, IS has clear socioeconomic and environmental advantages compared to P2C. Besides the points outlined in the previous sections, IS could improve Brazil's image as agricultural producer (which could provide greater competitiveness to enter niche markets or to export to places with stricter regulations) and increase wood supply in the region (currently below the demand of grain driers and steel production mills in Mato Grosso). The reduction of risk achieved through IS due to the diversification of the production portfolio and productivity improvement in the long run is an additional benefit – particularly the decrease of income seasonality and the higher livestock productivity throughout the entire year (including the dry season, when the carrying capacity of pastures tends to be lower).

The diffusion of P2C is already happening at a high pace and is expected to continue over the next decades irrespective of direct incentives. The expansion of IS may also start happening organically in the future as farmers are exposed to the technology and start acknowledging their potential benefits, but at this point – and given the higher complexity of crop-livestock-forest integration – IS diffusion requires active efforts from the Brazilian Government. This includes not only credit provision but a group of enabling conditions related to credit access, information diffusion and capacity building, as revealed in chapters 3 and 4. The fact that farmers have different motivations to engage in P2C or IS suggests a flaw in the assumption that IS is a further step in the agricultural intensification process relative to P2C and that the transition to it will necessarily happen.

The existing incentives aimed at IS adoption have not yet succeeded in promoting it at a wide-scale. As highlighted in chapters 3, most IS do not involve forestry, which reduces the capacity of IS to promote diversification, ensure animal welfare and mitigate climate change. Besides, the diffusion of iCL has mostly happened near soy areas and includes a limited participation of ranchers. The following sections summarize policy recommendations identified throughout our study – in particular with respect to credit, as highlighted in Chapter 5 – and other opportunities for improving the effectiveness, efficacy and equity of P2C- and IS-based agricultural intensification processes in Mato Grosso.

6.2.1. **Inclusiveness of intensification processes**

Intensification technologies generally require upfront capital investments and exhibit economies of scale, usually being adopted by wealthier and less indebted producers first. While this should reduce the cost of implementation, it may promote the concentration of landholdings (Cohn et al., 2011). A major challenge concerning agricultural intensification in Mato Grosso is to ensure that it does not compromise the livelihoods of less capital-intensive, smallholder farmers.

Chapters 2 and 3 revealed that both IS and P2C have been mostly adopted by medium-large farmers. The displacement of smallholders to areas where land prices are lower is actually an ongoing process. Increasing land prices in areas which are suitable for soybean cultivation has led to speculation and been driving a large portion of P2C selling contracts, for example. The livestock sector in Mato Grosso is already highly concentrated at the end of the supply chain, as three slaughterhouses (JBS, Marfrig and Frialto) hold 15 of the 18 major slaughterhouses in Mato Grosso) (Strassburg et al., 2013). Whether this situation will be exacerbated is ultimately a function of households' possibilities and preferences given economic and institutional circumstances.

As chapter 2 revealed, the decision to rent or sell land through a P2C contract may be taken, among others, by ranchers who lack the money and/or know-how to invest in farming. In such cases, credit and training could be incentives for the rancher to engage in IS instead of P2C (either by doing it himself, as it is currently done in Mato Grosso, or in partnership with a farmer). That way, the rancher would not be displaced nor have to leave the business, and the environmental gains would be greater for the entire society. Technical and financial support might not be sufficient to ensure the participation of less capitalized producers in the intensification process, but nonetheless contributes to it.

Although farmers and ranchers would benefit from technical assistance and training in management operations as well as the financial aspects of business management, efforts should be concentrated on the latter for two reasons. First, ranchers tend to be more conservative and less open to agricultural innovations; in all three studies, we saw that ranchers' socioeconomic indicators are the most discrepant from those who so far participated in intensification. Second, the involvement of ranchers is crucial for the achievement of the Federal Government's goal to increase productivity in currently degraded pastures.

According to chapters 2 and 3, households' perceptions of risk, risk attitudes and risk management strategies usually constitute a major factor influencing short- and long-term decisions, and might play a major influence on the occurrence of P2C. Sources of risk included climatic, market, institutional, production, environmental and personal risks (Hardaker 2004). The relative importance of each of these sources depends on farmers' motivations/goals, characteristics of the farm and the farmers themselves, and information acquisition and the learning process (Greiner et al. 2009, Cardenas & Carpenter 2013). In that sense, the provision of insurance and other mechanisms for risk minimization currently absent from the ABC credit program could encourage more producers in Mato Grosso to intensify production in their farms. Our findings also suggest that insurance and other mechanisms able to ensure a minimum remuneration for timber products would be particularly helpful when forestry is a component of the IS. Besides entailing a longer payback period than that of crop or livestock, trees limit farmers' flexibility to shift back to the original activity just like in agroforestry systems (Pattanayak et al., 2003). According to Strassburg et al. (2013), even if sustainable agricultural intensification measures were subsidized, the private sector should be provided with risk reduction mechanisms.

6.2.2. Incentives to promote the shift from specialization to integration

Agricultural intensification through IS depends on the concurrent implementation of policies in different areas. The fact that low technical know-how was a barrier to adopt IS and to access bank loans provided through the ABC credit program is evidence that credit provision alone is not sufficient and highlights the need to think of coordinated policies.

Financial support

Producers' decisions to adopt IS may result from their aim towards long-term sustainability. In practice, however, the surveys conducted throughout this work suggest that input and output prices are often the primary drivers of land use decisions. Even though IS is being actively promoted by the Federal Government through the already mentioned ABC Plan, the higher profitability of soy is often what determines the adoption of iCL and P2C.

At the same time that market conditions cannot be ignored if continued adoption is to be secured, wide-scale adoption of IS and other sustainable practices must be facilitated through financial support mechanisms and increased producers' awareness of their long-term benefits. For cases where agricultural intensification leads to improved yields and increases labor requirements on existing agricultural systems, Maertens et al. (2006) argue that "policies subsidizing yield-increasing technologies while taxing laborsaving technologies" could be helpful. This is particularly relevant considering that, in a scenario where soybean prices are continuously increasing, the dissemination of P2C will be particularly sensitive to variations in input and output prices (which might ultimately favor P2C over IS). The causes behind it may also include the initial investments related to forestry, when applicable, and high opportunity costs. While P2C adopters cultivate soy for several years until productivity falls due to soil degradation, IS adopters must forgo the short-term profits of cultivating soy in a larger area.

Payment for environmental services (PES) schemes constitute another financial mechanism that could increase the economic attractiveness of IS and boost its adoption. In considering the potential of Reduction in Emissions from Deforestation and Forest Degradation (REDD+), Bustamante et al. (2012, pp. 574) argue: "*On the international level, it becomes clear that the establishment of a broad, sustainable and long-term approach for REDD+, including all the forms of forest carbon (avoided deforestation, conservation of forest stocks and forest and pasture regeneration), could substantially favor the transition needed to a low-carbon livestock sector in Brazil (and in other countries). Its role should be seen as catalytic in relation to good practices and national programs, rather than an outright solution*." Considering that certain types of IS may turn carbon sources into carbon sinks (Carvalho et al., 2014), making these systems an eligible practice for carbon credit projects could offer an additional incentive for IS adoption.

Other mechanisms of financial support include preferential markets or premiums for agricultural products produced through more sustainable practices (Smith, 2008; Garrett at al., 2013; Newton et al., 2013). In that sense, the creation of certificates that distinguish soy bean cultivated in an integrated system and in conventional monoculture systems might be appropriate. In a previous study about the beef cattle sector in Brazil, Bustamante et al. (2012) state that selective remuneration is essential to stimulate investments in ranching and highlight the importance of retail in this context as the segment in which most value is added.

The ABC credit program

Although chapters 3 and 4 presented repeated evidence that credit availability has not been significantly associated to IS adoption in Mato Grosso, simulation results in Chapter 5 showed the potential contribution of the ABC credit lines on IS adoption in Mato Grosso. Measuring the impact of the ABC program on IS adoption can be tricky given the recent nature of the IS diffusion process and the fact that early technology adopters may have a unique propensity level to use credit. Still, as argued by Cohn et al. (2011, pp. 19), "*Credit availability at reasonable interest rates is essential for ranchers to adopt many new technologies, including more productive grass varieties and other types of pasture productivity improvements, or to buy the capital necessary to manage land more intensively (e.g. tractors, fences, etc.). The transition from more land-extensive to more land-intensive forms of ranching requires some combination of increased input usage in the form of fertilizer, lime, grass seed, supplemental feed, mineral salt etc.; upfront investments in machinery; infrastructure and pasture reformation; and increased labor costs. While the returns over the long run to more intensive practices may make their adoption rational, many ranchers and particularly small producers may struggle to obtain credit or access to the necessary financial capital to purchase inputs or machinery*". Combined with other preliminary evaluations of the ABC Plan (SENAR, 2013; IPAM, 2015) and the literature on the topic, our results suggest that credit for IS adoption must be better targeted and that barriers constraining access to credit must be overcome.

The analysis presented in chapter 5 explored five scenarios involving different credit conditions. It revealed that the highest cost-effectiveness of the ABC Program, assuming no transaction costs or other limitations to credit access, is associated to increased loans. Chapter 4 showed areas of Mato Grosso where IS does not yet occur, which could be used to guide credit issuance and the investment of other government resources aimed at scaling up IS adoption. Besides strengthening the ABC program in areas with no IS, policy makers should consider focusing resources where adoption is more likely to happen due to favorable logistics and supply chain infrastructure. Pursuing these two measures in parallel would certainly help increase the area under crop-livestock-forest integration, spread it towards sensitive areas and facilitate the participation of ranchers in the ABC program (which is currently low despite its importance for pasture rehabilitation).

An additional policy recommendation with respect to the environmental outcomes of the ABC credit program is that loans should be made conditional on the farmer's commitment that rotation among the different components of IS happens regularly and according to a minimum frequency that allows for nutrient replenishment in the soil. As it currently stands, the ABC Plan does not specify a minimum rotation frequency for each IS configuration nor requires monitored evidence of carbon accumulation as above and below ground biomass. Assuming that the "optimal rotation frequency" is the one that balances environmental and socioeconomic factors so as to maximize productivity for the longest period of time possible, a policy recommendation could be to create an index that weights maximization of a system's environmental benefits and farmers' utility.

Technical assistance

The adoption of IS implies the implementation of a more sophisticated management system, including periodic rotation of species. For this reason, IS requires more know-how and technical expertise – especially when forests are involved, as revealed in chapter 2. Besides policies focused on capacity building amongst producers themselves, which are needed given local farmers' lack of tradition with integrated systems, other interventions related to the improvement of rural extension services and multiplier agents (for example through show cases) could be of great help. Besides the need to improve the quantity and quality of technical support, it is important to make sure that the process of technology transfer and measures to enhance technical assistance is based on local farmers' demands (which may change over time) and incorporates the knowledge on agricultural innovation generated by those adopting the technology first.

Supply chain infrastructure

As highlighted in chapter 4, the existence of well-developed supply chain infrastructure is key to scale up IS adoption given the stricter requirements of soybean farming as compared to cattle ranching. Such requirements include the presence of storage facilities, processing units, distribution logistics and marketing, and are especially relevant in a state like Mato Grosso where infrastructure is geographically concentrated and/or saturated. However, the mere improvement of the supply chain infrastructure may lead to the expansion of P2C as well and will not necessarily favor iLPF; in other words, a well-developed supply chain infrastructure is almost like a necessary but insufficient condition for the dissemination of IS, and therefore must be combined with other interventions such as territorial zoning.

The need to improve the supply chain infrastructure for forestry activities deserves to be emphasized as an important measure to leverage investments in trees as part of integrated systems. The difficulty to process, transport and commercialize timber in most of Mato Grosso was frequently mentioned by local farmers surveyed during the study presented in chapter 3. Unless policies that provide incentives for the maintenance and improvement of roads, construction of silos, etc. are in place, producers might not be willing to invest in remote areas near degraded lands (which is precisely where IS would be most helpful). Fiscal incentives and tax exemption could help attract capital and kick-off a process of agglomeration economies (Fujita & Thisse, 2002).

Research & Development

Although P2C leads to a well-known system (i.e. soy cultivation), some basic information on the biophysical, managerial and financial aspects of the conversion from pasture to soy is still lacking. This includes the optimal scale of conversion from a cost-benefit analysis in different regions of Mato Grosso, the impact of previous uses of the soil on soy productivity over time, among others.

The uncertainties are even more pronounced when it comes to IS, given the diversity of systems, the synergistic effects between their components, and the interactions between these components and the ecosystem. From a natural sciences perspective, that includes the effect of fertilizer residues across crop/grass cycles, species rotation on productivity, optimal shading on the productivity of certain crops and grasses and the effects of species rotation on fertilizer and herbicide requirements. Previous studies have attempted to explain and measure some aspects of the interactions between IS and the ecosystems, such as those by Carvalho et al. (2010) and Franzluebbers & Stuedemann (2014), however very few studies explore those interactions in Mato Grosso. Little is known about the effects of grazing intensity and grass-crop rotation on water quality, tillage effects on C sequestration, stability under changing climate conditions, shade on the micro-climate and consequently on the productivity of certain species, optimal management for above and below ground biodiversity, complex soil dynamics, provision of other ecosystem services across various places/contexts, comparative advantages of different IS configurations for climate change mitigation and the rotation frequency implied must be further explored.

From a social sciences perspective too, many aspects of IS still need to be explored. Regarding IS adoption, this includes the exact requirements in terms of labor and other inputs, farmers' investment profiles and what combinations of assets determine the propensity of IS adoption, risk perception attached to changes in business as usual, and farm succession and its influence on IS. There is no agreement as for the best way to evaluate IS feasibility, short- vs. long-term costs and benefits of IS relative to other options (opportunity costs), rates of return on investment, availability of instruments to deal with risk, the role of cooperation between producers and other agents, the exact influence of neighbors and networks on IS adoption, role of information and risk perceptions, or the existence of new production systems happening that influence IS supply and demand. Uncertainties about farmers' decision-making process (including farmers' utility function, non-productivity utility sources, influence of culture/professional identity on risk perception, gender issues, knowledge and social capital) are particularly unknown.

Chapter 2 offered valuable insights into some of these aspects. Given the impossibility to measure each of them and the importance to understand how farmers' perception of new technologies, chapter 2 relied on reported instead of observed parameters. However, several remaining uncertainties lead to skepticism among rural producers and represent a barrier to behavioral change, especially when the incorporation of a complex technology like IS is at stake. Although generalizable facts about biophysical or economic aspects of IS do not exist, more research on the topic is paramount to IS wide-scale adoption. This is particularly true in an agricultural setting like Mato Grosso, where farmers have traditionally practiced monoculture and single crops (such as soy and cotton) represent attractive options due to their high profitability.

As argued by Balbino et al. (2011), the complexity of IS requires a new methodological framework able to address the individual and synergistic effects of IS' components. That entails long-term experiments that capture the biological cycle of the different species involved and the time necessary for the stabilization of the system as a whole. A multidisciplinary, systemic approach that includes researchers from the biophysical and socioeconomic fields is key, as existing experiments are mostly isolated and consist of short-term cases.

Concerning integrated forestry, it is worth emphasizing that only IS involving very few tree species are eligible for ABC credit due to limited information on the growth rate and productivity of other species. This poses a barrier to the inclusion of forests in IS since bank agents in charge of issuing ABC loans lack the technical parameters against which farmers' requests for credit can be assessed. Besides constituting a missed opportunity to increase IS adoption in Mato Grosso and achieve a much higher GHG emission reduction, limited information on local tree species might also lead to the replacement of local by non-local species and consequent biodiversity loss.

Other incentives

Brazil has new incentives for low-carbon agricultural practices but very few penalties that would change the relative profitability of integrated versus conventional production systems. On the one hand, measures able to decrease the attractiveness of conventional systems include decreasing direct price supports and mandates for single commodities, as well as creating carbon and pollution taxes. On the other hand, measure able to increase the attractiveness of IS include increasing incentives to soil conservation practices, establishing marketing rules and differentiability, identifying strategies and/or developing technologies that could increase the relative profitability of IS, reducing the bureaucracy associated to hiring labor and promoting capacity-building on IS (which is particularly important for cases involving labor-intensive IS types, providing insurance and other risk-mitigation mechanisms, and ensuring policy stability and legislation enforcement.

6.2.3. **The establishment of IS through partnerships**

Encouraging producers to engage in IS instead of P2C through the establishment of partnerships between specialized farmers and specialized ranchers could be beneficial from the individual and societal perspectives. As discussed at the end of chapter 3, such partnerships could help scale up iCL adoption while also ensuring the engagement of ranchers in IS. The mutual benefits for farmers and ranchers would include lower transaction costs, knowledge exchange and cost sharing for the implementation.

The decision to engage or not in either P2C or IS depends on the farmers' possibilities and preferences to undertake the transition entirely or doing it together with a peer. That is precisely where contracts, official and informal bodies responsible for monitoring the enforcement of contractual obligations, as well as other land market institutions become crucial in determining transaction costs (Deininger & Feder, 2009). Ultimately, this determines the feasibility of shifting from specialized to integrated production models. In that sense, our policy recommendations revolve around tackling the limitations of Mato Grosso's land market, e.g. by reducing speculation and the bureaucracy that applies to formal land transactions (Jepson, 2006; Brannstorn, 2012; Assunção & Chiavari, 2014). As highlighted in chapter 2, well-functioning land markets can play an important role in promoting efficient land use. Finally, the provision of incentives such as tax exemptions, access to insurance mechanisms in the case of contract breach and membership to associations through which producers could encounter potential partners would certainly encourage partnerships.

6.3. Applicability of the results of this thesis

By quantifying, describing and interpreting major drivers and constraints associated to the adoption and diffusion of IS and P2C, this thesis has generated several results relevant to policy making. Such diagnostic is particularly relevant to the monitoring of the ABC Plan and the agricultural technology diffusion processes taking place in Brazil. Much of the content presented here has already been used in recent Embrapa publications (Isernhagen & Guerin, 2013; Behling et al., 2014; Garrett et al., 2015).

Five ongoing research projects have benefited from the results of this thesis, including: Carbon-optimized land management strategies for southern Amazonia - CarBioCial (German Federal Ministry of Education and Research - BMBF); "Do Integrated Systems Reduce Climate Risk in Tropical Savannahs: The Cases of Mozambique and Brazil" (International Fund for Agricultural Development / Climate Change, Agriculture and Food Security); "Improving agricultural practices for sustainable development" (United States National Science Foundation); "Institutional and Behavioral Influences on Agricultural Technology Adoption: The Case of Pasture to Cropland Conversion in Brazil" (University of California – Berkeley, Energy Biosciences Institute); and "Standardization Methods, Software Development and New Approaches to the Economic Evaluation of Integrated Crop-Livestock-Forest Systems" (Embrapa Agrossilvopastoril)[11].

6.4. Limitations of this study

Besides specific data limitations related to each of the analyses presented in chapters 2 to 5, three general limitations of this study must be acknowledged. The first is related to the spatial and temporal comprehensiveness of the analyses presented. Both IS and P2C are still

[11] In Portuguese, "Padronização de Metodologias, Desenvolvimento de Software e de Novas Abordagens para Avaliação Econômica de Sistemas de Integração Lavoura-Pecuária-Floresta".

starting to disseminate, so running the same analysis for a longer period of time and looking into technology dissemination on a regular basis is advisable. Space and time are extremely important when it comes to the assessment of a technology diffusion process (Adger et al., 2005) given that the rapid developments are taking place in the region, especially in frontier areas (Walker et al., 2002; Maertens et al., 2006; Byerlee et al. 2014). Besides, the government is putting extra effort in promoting IS, e.g. through the establishment of Embrapa experiments, and the farmers interviewed throughout the study are mostly pioneers and early adopters who behave differently than later adopters. Even though this study provides important lessons at a point in time when policy evaluations may still serve as guidance to improve the ABC credit program, the elements above must be taken into account before results are generalized.

The second limitation concerns the impossibility to assess the synergistic effects between IS components. Conducting the same analysis over a larger area and a longer time period would also allow for more accurate conclusions on those effects. As previously argued, it is too early to make exact inferences about the cumulative effects of IS on soil fertility or GHG emissions.

The third limitation concerns the analyses and parameters employed. A direct comparison between P2C and IS using the same analytical framework could have generated more straightforward comparisons in terms of costs and benefits of the two intensification pathways. The biophysical attributes and transportation costs which are already measurable and known to interfere in land use decision making (Lambin et al., 2001; Turner et al., 2007; Álvarez Martínez et al., 2011) were not the focus of the analyses on IS adoption but should be refined in future research. Soils in Mato Grosso are acidic and poor in nutrients, but tolerant seeds developed by Embrapa and inputs that can correct for that (e.g. fertilizers and lime for pH) have become widely disseminated. The fact that the growing season is long enough to allow for a second crop is a comparative advantage of MT (VanWey et al., 2013) which often compensates for higher fertilizer prices in the region (Cohn et al., 2014). Yet, small-scale biophysical variations may pose impediments to agriculture; soil structure influences its capacity to hold water and affects soil moisture and water availability for plants (Couto et al., 1997; Farias et al., 2007; Vera-Diaz et al., 2008), and rainfall tends to be more abundant at the fringe of the rainforest (Werth & Avissar, 2002; Aragão, 2012), for example.

6.5. Insights for future research

The successful implementation of policies aimed at promoting specific agricultural intensification pathways requires a deep understanding of the drivers and barriers to LUC and the interplay between them at the local and regional scales. Despite the socioeconomic and environmental relevance of P2C and IS for Mato Grosso, Brazil and the world as a whole, critical gaps in information and knowledge must be addressed with urgency. Many of these gaps have already been outlined in earlier sections. Still, some general points deserve to be emphasized.

The assessment of P2C and IS as two agricultural intensification strategies must be done relative to other systems. In that sense, it is important to couple the findings presented here with those of other studies. Likewise, the methods used in this and other research initiatives must be compared if the evolution of the IS/P2C dissemination processes is to be fully understood.

At least three topics would be interesting to investigate more deeply. The first consists of the influence of biophysical conditions (such as soil types) on the adoption of specific IS configurations and monitor it over the long run through data measured at the plot level, especially when the processes of technology adoption and diffusion reach stability and results are less prone to biases. The reassessment of IS adoption determinants in five or ten years could serve as a starting point to answer whether results obtained so far should be generalized and to what extent. The second refers to the advantages and disadvantages associated to alternative IS arrangements (such as shared tenancy or cooperation between specialized farmers) are another research avenue to explore. That could help overcome the IS adoption constraints identified in the study (including limited investment capacity, labor availability or know-how necessary to introduce a new farming activity). The third concerns the impact of IS diffusion among small-holders. The fact that IS are more widely spread among large farmers is positive considering that the main goal of the ABC Plan is the reduction of overall GHG emissions; after all, the share of small-scale holdings in Mato Grosso's overall GHG emissions is relatively small because they concentrate less land and usually employ less intense field operations than large farms. However, considering environmental and economic benefits potentially promoted by IS, it would be interesting to design small-scale business models that can be used on small-scale farms – not only in the cases where IS could promote a significant improvement such as in dairy farms, but also due to its potential impacts at the regional level.

The identification of specific impacts of agricultural development pathways depends on more empirical research. At the same time, modeling efforts should better incorporate non-linear systems, threshold effects and other complex aspects of land use and management (Lee & Barrett 2001). This could help better assess different agricultural intensification measures and understand the cumulative effects of IS on nutrient cycling, aggregate labor supply and demand, as well other aspects that this thesis could not completely elucidate.

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Author's declaration

I hereby declare that this doctoral thesis is a result of my own work and that no other than the indicated aids have been used for its completion. All quotations and statements that have been used are indicated. Furthermore, I assure that the work has not been used, neither completely nor in parts, for achieving any other academic degree.

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