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**Land use change and land use displacement dynamics  
in Mato Grosso and Pará, Brazilian Amazon**

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## **Abstract**

Global demands for agricultural commodities such as food, feed, fuel, and fiber have become a major threat for some of the most valuable natural ecosystems in the world. The rapid expansion of the agricultural sector in Brazil, fueled by global demands for soybeans, contributed to the large-scale destruction of globally valuable tropical and savanna ecosystems. Most deforestation, however, was caused by the conversion of forest for pastures, raising concerns about linkages and displacement processes between soybean expansion and cattle ranching. In 2004, governmental strategies in Brazil, backed by a zero-deforestation commitment of the major soybean-trading companies in 2006, marked a turning point in deforestation, followed by decreasing rates of forest loss.

This thesis aims to contribute to the understanding of the spatial and temporal dynamics of soybean expansion and cattle ranching, driving deforestation under changing environmental governance in Brazil. The Brazilian federal states Mato Grosso and Pará encompass one of the most dynamic frontiers of soybean cultivation, cattle ranching, and deforestation in the Amazon. In this region, land use displacement processes refer the conversion of pasture for soybean in a particular region followed by cattle ranching driving deforestation at another location. This process was assessed at regional and at property scale. Publicly accessible data on past land use changes, changes in agricultural production, and spatially explicit property information were employed to analyze land use and land use displacement dynamics at the interaction between cattle and soybean production. Scenario analysis was applied to identify regional and subregional dynamics of land use change that were linked to the expansion of agricultural production.

The results of this thesis indicated regional and local land use dynamics and land use displacements to be affected by environmental governance. Distal displacement processes between soybean expansion in Mato Grosso and deforestation in the Amazon, particularly along the BR-163 highway, were significant, contributing to deforestation, but declined subsequently to the implementation of the environmental policies. Likewise, deforestation at property level declined following the policy implementations. However, displacement deforestation at property level challenged the effectiveness of the zero-deforestation commitment of the soy industry. Cross-scale scenario analysis of potential future land use and deforestation along the BR-163 highway emphasized the importance of subregional dynamics and risks of deforestation due to the expansion of cattle ranching. These findings suggest that better control and reduction of future deforestation require to account for the interactions between soybean and cattle production. Integrating efforts between supply chain actors, the soybean and beef purchasing companies, and the government enforcing policies aiming to control deforestation appear to be crucial measures to address illegal deforestation.



## Zusammenfassung

Die globale Nachfrage nach Agrarerzeugnissen gilt als eine der zentralen Ursache für den Verlust der weltweit wichtigsten Ökosysteme. Auch in Brasilien haben Nahrungsmittel-, Viehfutter-, und Bioenergieproduktion, speziell die rasche Ausweitung der Sojaproduktion, zur großflächigen Abholzung tropischer Wälder sowie zur Umwandlung von Savannenökosystemen geführt. Zumeist werden hierbei neu gerodete Flächen als Rinderweiden genutzt und vormaliges Weideland für den Sojaanbau umgewandelt. Diese Entwicklung führt zu der Annahme, dass die Ausweitung der Sojaanbaufläche indirekt, durch die Verdrängung der Rinderproduktion, für die Rodung verantwortlich ist. Mit der Einführung des Aktionsplans zur Kontrolle und Verhinderung von Abholzung im Jahr 2004 und die Selbstverpflichtung der Sojahändler, nur das Soja abzunehmen, für dessen Produktion kein Regenwald gerodet wurde, kam es zu einer Änderung von Landnutzungsdynamiken, in dessen Folge Regenwaldzerstörung zurückging.

Vor diesem Hintergrund zielt die vorliegende Dissertation darauf ab, ein vertieftes Verständnis der Wechselwirkungen zwischen Soja- und Rinderwirtschaft zu erlangen. Im Fokus stehen hierbei die räumlichen und zeitlichen Dynamiken von Landnutzungsveränderungen und Landnutzungsverdrängung im Amazonas. Konkret werden mit den Bundesstaaten Mato Grosso und Pará die dynamischsten Regionen von Sojaanbau, Rinderwirtschaft und Entwaldung analysiert. Für diese Bundesstaaten untersucht die vorliegende Dissertation die Landnutzung und Landnutzungsverdrängung im regionalen Kontext, auf Grundstücksebene und mithilfe der Szenarienanalyse. Die Datenbasis bilden öffentlich zugängliche Statistiken zur landwirtschaftlichen Produktion, Landnutzungs- und Abholzungskarten sowie Katasterdaten.

Die Ergebnisse zeigen, dass die Strategien der brasilianischen Regierung zur Verringerung der Abholzung Einfluss auf die regionalen und lokalen Dynamiken der Landnutzung und Landnutzungsverdrängung hatten. Durch die großflächige Ausweitung der Sojaanbauflächen hervorgerufenen regionale Verdrängungsprozesse, die in Mato Grosso insbesondere entlang der BR-163 Straße zur Abholzung führten, haben sich nach der Implementierung der verschiedenen Umweltschutzstrategien verringert. Auch die Abholzung auf einzelnen Grundstücken in Mato Grosso ging zurück. Zugleich zeigt die Analyse, dass die Selbstverpflichtung der Sojaindustrie durch indirekte Abholzung, d.h. Sojaanbau expandiert auf Weideland, gefolgt von Abholzung für Rinderweiden, untergraben wird. Die Ergebnisse der skalenübergreifenden Szenarienanalyse stellen die Region entlang der BR-163 als besonders dynamisch dar. Zukünftig scheint die Region speziell der weiteren Expansion der Rinderwirtschaft ausgesetzt.

Insgesamt legen die Ergebnisse nahe, dass auf effektive Verringerung der Abholzung abzielende Strategien die Wechselwirkungen von Rinderwirtschaft und Sojaanbau beachten müssen. Dies erfordert eine verstärkte Zusammenarbeit der verschiedenen Akteure der Rinderwirtschaft, der Sojaindustrie und der staatlichen Organisationen.





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Chapter I:  
**Introduction**

## **1 Introduction**

### **1.1 Global Environmental Change and Land System Science**

The large-scale transformation of natural ecosystems for agricultural production is one of the most profound human-induced changes of the last three centuries (Ramankutty and Foley, 1999). Today, 75% percent of the earth surface show evidence of alteration caused by human land use (Ellis and Ramankutty, 2008). Herein land use is defined as the purpose for which humans exploit the surface of the earth and its biotic and abiotic components (Lambin et al., 2006). Agricultural land use dedicated to food production, animal fodder, bioenergy crops, and other commodities covers approximately 38% of the earth surface (Foley et al., 2011). Overall, these changes left no ecosystem free of human influence (Vitousek, 1997; Turner et al., 2007). In fact, the magnitude of human alterations of the earth system has become the dominant force of global environmental change (Crutzen, 2002; Steffen et al., 2007).

On the one hand, these transformations have contributed to substantial net gains in human well-being and economic developments. They include global increases of food supply for a growing world population, increasing income and wealth and rising life expectancies (Rhoe et al., 2005). On the other hand, the human-induced changes led to trade-offs between multiple ecosystem services causing degradation, including irreversible alterations, of ecosystems. Deforestation for agricultural expansion, for example, affect local, regional, and global climates (Gedney and Valdes, 2000; Alves et al., 2017; Jiao et al., 2017). The related habitat loss contributes to the global biodiversity loss (MEA, 2005). Furthermore, extensive fertilizer use resulted in the degradation of local and regional water quality (Matson et al., 1997; Bennett et al., 2001) and land degradation is estimated to cause a loss of 1-2.9 million hectares of arable land per year (Wood et al., 2000; Cassman et al., 2005; Lambin and Meyfroidt, 2011). According to estimates on human population increases (Gerland et al., 2014) and shifts in consumption habits (Kearney, 2010; Reisch et al., 2013; Tilman and Clark, 2014) there will be an additional demand of 70-100% of food until 2050 (Bruinsma, 2009; Godfray et al., 2010). Combined with increasing demands for bioenergy (Beringer et al., 2011), this will require between 0.12-1 billion hectares of additional agricultural land until 2050, depending on the efficiency of production, future diets, food wastage, and food-to-feed efficiency in animal production (Kendall and Pimentel, 1994; Tilman et al., 2001;

Godfray et al., 2010). The cumulative effect will massively impact the environment, creating profound challenges for human welfare and environmental conservation (Tilman et al., 2001; Laurance et al., 2014).

Land System Science addresses this challenges, aiming to understand causes and consequences of past and possible future changes on the terrestrial surface of the earth (Lambin et al., 2006; Turner et al., 2007; Verburg et al., 2015). It aims to identify and to balance trade-offs between multiple ecosystem services, to find pathways towards more sustainable use of land (Foley et al., 2005, 2005; Verburg et al., 2015). Herein, land-system changes are understood as the direct result of human decision-making, ranging from local landowner decisions to national-scale land use planning, global trade arrangements and feedbacks between those dimensions (Verburg et al., 2015). Changes in land use are often explained within the dimensions of proximate and underlying causes. Proximate causes refer to the physical action and direct use of land. Underlying causes are the fundamental forces that underpin these proximate causes. They operate more diffusely and relate to the complex of economic, political, institutional, technological, demographic, cultural, and social factors and their interactions that constitute the human environmental relations (Geist and Lambin, 2002, 2004; Geist et al., 2006; Meyfroidt, 2016). Herein, “causes” might be best understood to be “contributory” or “combinatory”, in which the combination and feedbacks between causes explain the resulting land use change (Meyfroidt, 2016).

Strategies for nature conservation often refer to land use zoning, restricting the expansion of land uses to specific zones, or agricultural intensification, thought to spare land for nature by increasing the agricultural output per unit land (Lambin and Meyfroidt, 2011). These strategies are increasingly undermined by distal relations between land use changes. Globalization, facilitated by trade liberalization and decreasing transportation costs, has led to an increasing separation between the location of consumption and production (Lambin and Meyfroidt, 2011). Recent expansions of agricultural production have often occurred in tropical countries, where low production cost and few environmental regulations allowed quick responses to global demands for agricultural commodities (Gibbs et al., 2010). Most often, agricultural expansion occurred at high environmental costs, converting tropical forest, shrubland and savanna ecosystems for export oriented commodities, such as soybean, sugarcane and oil palm (Grau and Aide, 2008; Gibbs et al., 2010). One of the regions that has experienced extensive agricultural growth is Latin America, where demands for soybean as animal fodder, mostly exported to Chinese and European markets, fueled the development

of a large export-oriented industrial production system (Dros, 2004; Grau and Aide, 2008). This expansion led to a pervasive conversion of some of the most significant forest and savanna ecosystems that sustain exceptional species richness store much of the earth biomass carbon and are a major element of the global hydrological cycle providing critical services for local, regional and global climates (DeFries et al., 2002; Grau and Aide, 2008; Laurance et al., 2014; Jiao et al., 2017). Even though large expansion already occurred, future agricultural expansions are projected to be highest in Latin America (Graesser et al., 2015; Alexandratos and Bruinsma, 2016).

Brazil is one of the key countries in Latin America, where the expansion of export-oriented agriculture, on the one hand facilitated economic development, but on the other hand caused direct and indirect loss of forests and savanna ecosystems in the Amazon and Cerrado biomes (Grau and Aide, 2008; Arima et al., 2011; Macedo et al., 2012; Andrade de Sá et al., 2013). Indirect deforestation describes the conversion of forest caused by a displacement of land use from one location, driving the expansion of the same land use in another location (Arima et al., 2011; Lambin and Meyfroidt, 2011; Richards, 2012a; Andrade de Sá et al., 2013). In Brazil soybean and sugarcane expansion in areas previously occupied by pastures has been associated with pasture displacement causing deforestation in the Brazilian Amazon forests (Arima et al., 2011; Andrade de Sá et al., 2013; Richards et al., 2014; Jusys, 2017). Scenario analysis suggested that the indirect environmental effects of future expansions of soybean biodiesel and sugarcane ethanol production might surpass the carbon savings achieved by using biofuels instead of fossil fuels (Lapola et al., 2010a). This renders land use displacement processes critical for policies on land use planning.

Even though advances in understanding the impact of land use displacements on scenarios of deforestation and land use changes have been made (Lapola et al., 2010a), large uncertainties between regional and local land use change dynamics and processes remain (Brown et al., 2013). Dalla Nora et al. (2014), for example, evaluated key elements of scenario analysis on deforestation in the Brazilian Amazon. They found that most models failed to capture the amounts and dynamics of deforestation of the recent decades. They suggested that integrating land use change models across scales might overcome current challenges to represent the complex dynamics of land use changes, dependent not only on local but also on regional and global processes. Similarly, other researchers stressed the need to enhance the understanding of dynamics and feedbacks between scales. To address these challenges model coupling has often been suggested to advance the representation of cross-



scale land use dynamics (Brown et al., 2013; Dalla-Nora et al., 2014; Verburg et al., 2015). While some coupled modeling approaches, combining different scales of analysis exists (Verburg et al., 1999; Moreira et al., 2009), further exploration of land use dynamics across scales is needed to advance the knowledge on dynamics, feedbacks and concepts of cross-scale modeling (Brown et al., 2013; Verburg et al., 2015).

## **2 Land use change, deforestation, and environmental governance in the Brazilian Amazon**

Understanding causes and dynamics of land use change and deforestation is particularly relevant for the Brazilian Amazon forest, which has experienced the world's highest annual loss of forest during the last decades (FAO, 2005, 2010, 2015). The Amazon forest as a whole constitutes the largest continuous tropical forest in the world (Skole and Tucker, 1993) and is one of the major components of the earth system (Malhi et al., 2008). It possibly hosts a quarter of the world's terrestrial species (Malhi et al., 2008), accounts for about 15% of the global terrestrial photosynthesis (Field et al., 1998), and the respective evaporation and condensation are engines of the global atmospheric circulation (Gedney and Valdes, 2000; Werth and Avissar, 2002). Most of the Amazon forest lies within the national boundaries of Brazil, representing about 60% of the Amazon biome (Figure I-1). In 2006, the Brazilian Amazon covered about 5.3 million km<sup>2</sup>, corresponding to 85% of its original extent (Soares-Filho et al., 2006). Past deforestation caused habitat destruction and biodiversity loss, and affected the local, regional and global hydrological cycles (Gedney and Valdes, 2000; D'Almeida et al., 2007; Foley et al., 2007; Malhi et al., 2008; Aragão, 2012; Davidson et al., 2012; Spracklen et al., 2012; Wearn et al., 2012; Steege et al., 2015; Zemp et al., 2017).

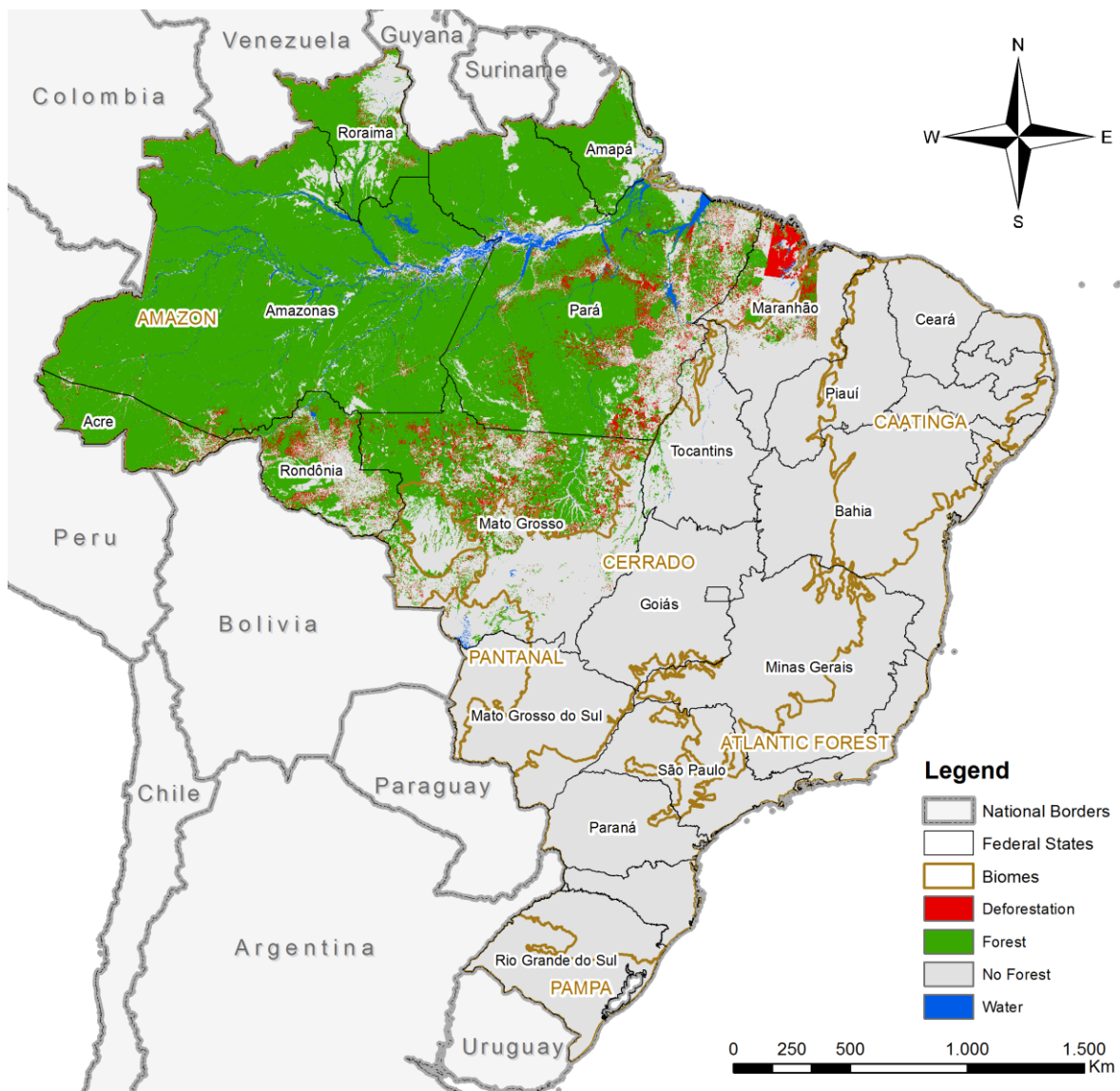


Figure I-1: Brazilian biomes, federal states, and deforestation in the Amazon between 2001 and 2012 (Source: INPE, 2014a; MMA, 2015)

Significant deforestation only started in the 1960s when large infrastructure projects motivated by political and economic factors, e.g., to secure the territorial integrity and to integrate the Brazilian hinterland into the national economy, opened up formerly remote forest areas (Mahar, 1990; Tritsch and Arvor, 2016). Migration and agricultural development of the region were supported by governmental programs, including agricultural credits, reduced taxes, and investments into infrastructure (Fearnside, 2002; Arvor et al., 2016). Land occupation in the Amazon occurred via spontaneous settlements and colonization programs, starting in the 1970s. Land titles were commonly assigned after one year and one day of occupation and the “effective” development of “unproductive” land. Even though environmental regulation already existed, i.e., the Brazilian Forest Code (Código Florestal,

1965) which regulated that each property in the Brazilian Amazon retains 50% of its area under forest (revised in 1996 to 80 %), these regulations were regularly disregarded. Land, not under “effective” use, i.e., natural forest, was considered unproductive and expropriated for new settlers. This conflicting interpretation between land tenure and environmental regulations, motivated farmers to deforest, commonly converting forest to pastures in order to reduce the risk of expropriation (Hecht, 1993; Alston et al., 2000; Puppim de Oliveira, 2008). Hence, cattle ranching as a proximate cause of deforestation was often a means to claim land, to obtain financial benefits related to different governmental programs, and for speculative gains on future land prices (Hecht, 1985, 1993; Fearnside, 2005). Furthermore, it provided economic flexibility, little labor, and held social and cultural values, in which cattle ranching and deforestation are positively associated with socioeconomic success and hard work (Hoelle, 2014; Zycherman, 2016). Deforestation in the Brazilian Amazon driven by speculative gains cumulated in 1995 (Figure I-2) when inflation rates surpassed 5 thousand percent in 1994 (Sachs and Zini, 1996; Fearnside, 2005). The monetary reform Plano Real, implemented in 1994, successfully halted inflation and made Brazil attractive for international investments (Fearnside, 2005).

Deforestation began to be sensitive to global prices for agricultural commodity since the late 1990s (Nepstad et al., 2006). Fueled by increasing global demands for soybean, technological advancements, and the development of adapted soy varieties, a large-scale expansion of mechanized crop production into the Cerrado and Amazon biome occurred (Spehar, 1995; Fearnside, 2001; Klink and Machado, 2005; Arvor et al., 2011b). Next to direct conversion of forest, soybean expansion most often occurred via the conversion of pastures (Macedo et al., 2012). While the relation between cattle and deforestation has been more or less stable, global soy prices have become increasingly related to deforestation. This supported the hypothesis on land use displacement describing the process of the conversion of pastures for soybean, followed by deforestation for pasture in the Amazon region (Barona et al., 2010). Nepstad (2006), for example suggested, that profits from soybean production drove up land prices, allowing cattle ranching to sell their properties at high profits and purchase new lands further north at the forest frontier regions. Similar hypotheses emerged with the expansion of sugarcane production in south-eastern Brazil, displacing cattle ranching towards the Amazon forests (Andrade de Sá et al., 2012; Jusys, 2017). These displacement processes may have been amplified by increasing profits from cattle ranching, supported by advancements in animal health, and increasing national and international demand for beef (Kaimowitz et al., 2004; Bowman et al., 2012; Bowman, 2016). Overall,

extensive, low input cattle ranching systems continue to dominate the Amazon biome, while market-oriented, intensified ranching systems gradually appear (Nepstad et al., 2006). Following these dynamics, the total Amazon cattle herd expanded by 169%, from 26 to 70 million animals between 1990 and 2007 (Bowman et al., 2012).

Decreasing deforestation rates in the Brazilian Amazon between 2005 and 2012 marked a turning point when environmental governance contributed to the reduction of deforestation (Figure I-2) (Nepstad et al., 2009; Nepstad et al., 2014; Assunção et al., 2015). Key strategies of environmental governance were aligned within the action plan to prevent and control deforestation in the Legal Amazon (PPCDAm). The PPCDAm focused on three main areas: land use zoning, enforcement of environmental laws, and strategic credit allocation. Between 2005 and 2007, 25 million hectares of conservation units and 10 million hectares of indigenous lands were designated (MMA, 2016). Enforcement of command and control policies was achieved by expanding the number and qualification of personnel at the Brazilian Institute for the environment and renewable natural resources (IBAMA), responsible for the enforcement of environmental law. The development and operational use of a near-real-time deforestation monitoring systems (DETER, DEdecção de desmatamento em Tempo Real) in addition to the existing monitoring program of annual gross deforestation (PRODES) allowed rapid detection and response to illegal deforestation activities (Assunção et al., 2013b; INPE, 2017). Strategic credit allocation made credits lending conditional upon the compliance with environmental laws. Additionally, a collective exclusion from credit allocation applied for those municipalities with the highest deforestation rates (Assunção et al., 2013a). Moreover, credit programs in support of more sustainable land use practices were created. One example constitutes the low carbon agricultural program supporting integrated crop-livestock-forestry systems in the Amazon (Gil et al., 2015; MMA, 2016).

One of the most important environmental laws in Brazil is the Brazilian Forest Code (Código Florestal, 2012). First implemented in 1934 it has been altered multiple times until its latest revision in 2012 (Código Florestal, 1934). The Brazilian Forest Code commits landowners to set aside native vegetation for conservation, and regulates the conservation of riparian areas and hilltops. In the Amazon biome, 80% of a property are required to be set aside from production. However, forest trading schemes between landowner and property size specific regulations apply (Código Florestal, 2012). The 2012 revision additionally institutionalized

the rural cadastre (CAR), aiming to provide the first complete database on land ownership in Brazil and intends to support policies to reduce deforestation (Código Florestal, 2012).

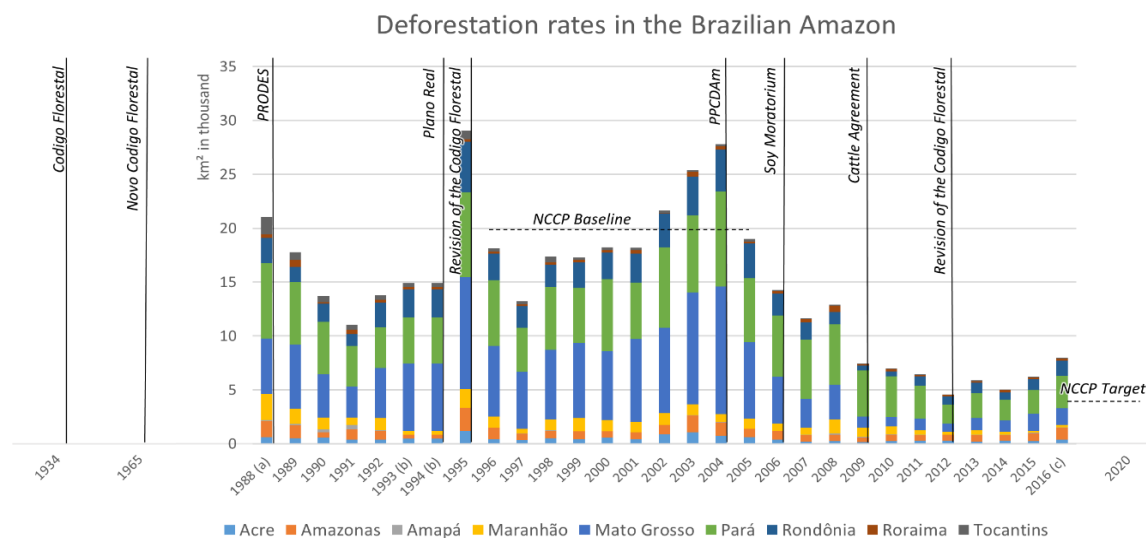


Figure I-2. Annual gross-deforestation estimates provided by PRODES, annotated by governmental and institutional agreements of environmental governance in the Brazilian Amazon (a: mean 1997-1998; b: mean 1993-1994; c: estimated rate)

In 2006 the major soybean purchasing companies committed not to purchase soybean produced from newly deforested areas in the Amazon. This commitment, termed the Soy Moratorium, was achieved following international concerns on the environmental impact of soybean production in the Amazon (Greenpeace, 2006; Gibbs et al., 2015). Since its implementation, evaluations of the Soy Moratorium suggested its effectiveness in decreasing direct deforestation for soybean production (Rudorff et al., 2011; Macedo et al., 2012). This success motivated pressure on the beef industry to ban deforestation from cattle raising. In 2009 major beef purchasing companies agreed within the MPF-TAC and the G4-Cattle agreement, not to purchase cattle raised on newly deforested areas (Greenpeace, 2009; Nepstad et al., 2014; Gibbs et al., 2016). However, monitoring the full lifecycle of cattle which often spend time at multiple properties prior to slaughter remains challenging, limiting its effectiveness in reducing deforestation.

Furthermore, Brazil pledged to reduce deforestation during the United Nations climate change conference in Copenhagen in 2009. The announced national climate change policy (NCCP) commits Brazil to reduce Amazon deforestation by 80% below its ten-year baseline average of 1996-2005 until 2020 (Nepstad et al., 2014). In view of the increasing deforestation rates of the last years, Brazil additionally announced at the United Nations

conference on biodiversity in Cancun in 2016 to rehabilitate and reforest 12 million hectares of degraded or deforested areas (Cannon, 2016).

### **3 Research Questions, Study Region and Objectives**

Increasing deforestation rates since 2012 challenge the effectiveness of the current strategies to reduce deforestation and to achieve the Brazilian national climate change policy targets (Figure I-2). This thesis aims to contribute to the understanding of deforestation process in the Brazilian Amazon by analyzing the interaction between soybean production, cattle ranching, and deforestation. The focus of the analysis was on the dynamics of land use changes and their interaction before and after the implementation of the action plan to prevent and control deforestation in the Legal Amazon (PPCDAm) and the Soy Moratorium. In-depth understanding of these interactions in the context of current policies is crucial to find effective strategies for forest conservation. Moreover, this thesis intends to contribute to the understanding of future scenarios of land use changes across scales for one of the hotspots of deforestation in the Brazilian Amazon.

This leads to the following research question:

*Research Question 1: How did land use and land use displacement dynamics change in relation to the implementation of the PPCDAm and the Soy Moratorium?*

*Research Question 2: How do scenarios of land use deviate between a cross-scale model-coupling approach and a subregional scenario quantification?*

The larger study region comprised the federal state of Mato Grosso and Pará, connected via the BR-163 highway (Figure I-3). Mato Grosso has experienced a large-scale expansion of agricultural production during the last decades and currently is the largest producer of soybeans in Brazil (IBGE, 2017). Areas under soybean cultivation expanded from 3.5 to 5.3 million hectares between 2000 and 2007 (Arvor et al., 2011b). The BR-163 highway connects the export-oriented, industrial agricultural production areas in Mato Grosso with the harbor in Satarém, Pará. (Figure I-3). Constructed as an export corridor in 1973 the BR-163 opened up vast areas of formerly remote forests traversing one of the highest bird

biodiversity regions in the Amazon (Nepstad et al., 2002). With advancing human migration and occupation of land along the highway, the BR-163 became one of the most active deforestation frontiers (Fearnside, 2007; Vieira et al., 2008; Pinheiro et al., 2016). Similarly, Mato Grosso has been a hotspot of deforestation, harboring half of all deforestation between 1990 and 2004 (Nepstad et al., 2014). Soybean expansion most often occurred via the conversion of pastures (Macedo et al., 2012). This led to the hypothesis that soybean expansion might cause indirect deforestation due to the displacement of cattle ranching activities along the BR-163 towards the inner Amazon (Nepstad et al., 2006; Barona et al., 2010). Overall, the BR-163 region represents a wide diversity of land use system, ranging from large-scale industrial agriculture systems in Cerrado and southern Amazon biome in Mato Grosso, to large cattle ranching systems around Guaratã do Norte, and extensive, low-input pastures system in Novo Progresso, southern Pará (Figure I-3). As one of the hotspots of deforestation and soybean expansion in the Amazon, this region qualifies as one of the most significant areas to analyze changes in land use dynamics and displacements effects associated with the implementation of the PPCDam and the Soy Moratorium.

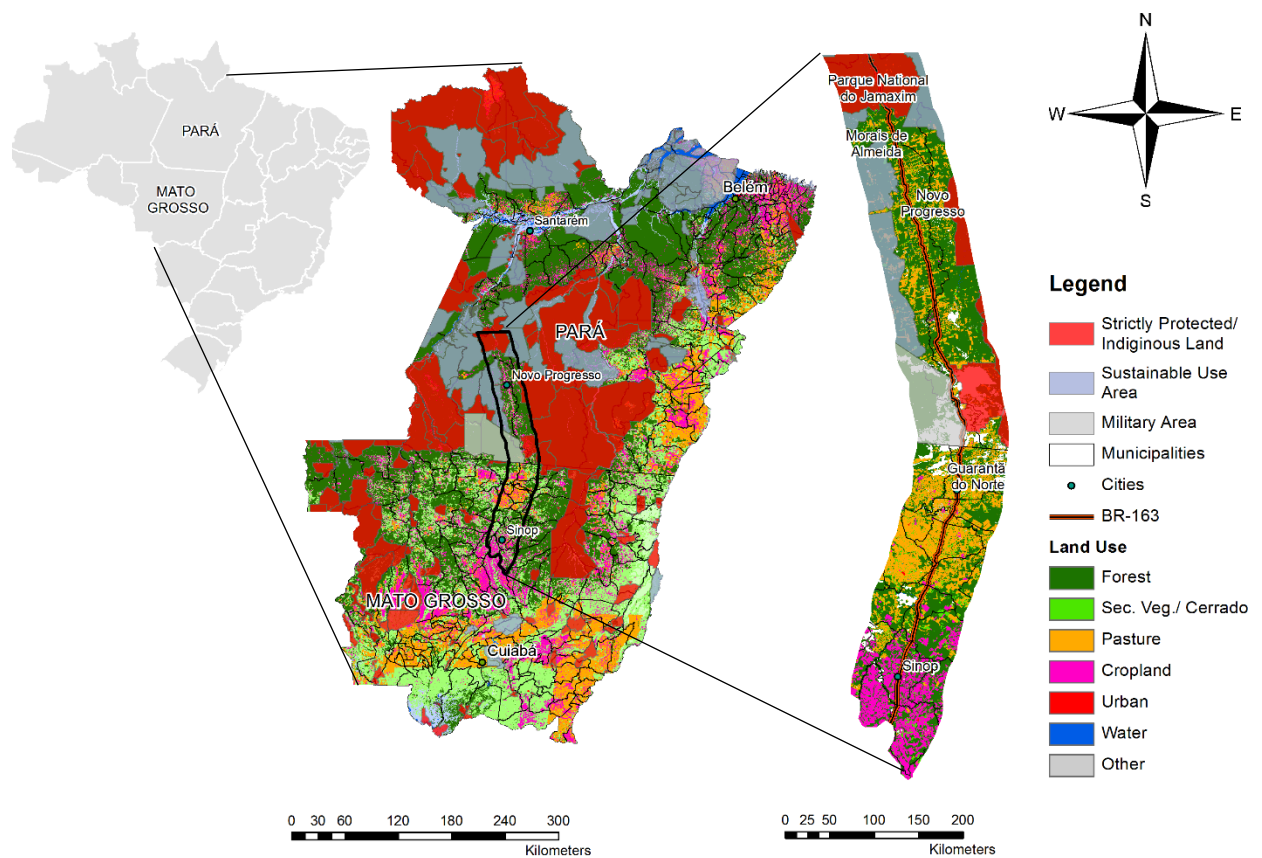


Figure I-3: Overview of the BR-163 corridor in Mato Grosso and Pará (Source: IPEA; GLCF, 2014; INPE, 2015; MMA, 2015; IBGE, 2015 )

The main objectives of the thesis were:

*Objective 1: To investigate the interaction and displacement dynamics between soybean expansion in Mato Grosso and deforestation for cattle ranching along the BR-163 before and after the implementation of the PPCDAm.*

This analysis aimed at regional displacement dynamics, based on annual agricultural census data for soybean and cattle expansion and annual gross deforestation estimates aggregated at municipality level. A panel regression approach was applied to estimate displacement effects between soy expansion in Mato Grosso and deforestation for cattle ranching along the BR-163 before (2001-2004) and after (2008-2012) the implementation of the PPCDAm. Moreover, a deforestation transfer ratio suggested by Gasparri et al. (2013) was calculated to better understand the direct relations between cattle or soybean production and deforestation along the BR-163 highway.

*Objective 2: To quantify on-property deforestation for soybean expansion, accounting for direct deforestation and indirect deforestation in perspective of the regulations of the Soy Moratorium.*

Following the observation that deforestation for soybean production considerably declined after the implementation of the Soy Moratorium, the question arose, if farmers expand their soybean production over pasture and deforest for cattle ranching instead. Using spatially explicit property data for the Amazon region of Mato Grosso and ten years of land use and cover information at a spatial resolution of 30×30m<sup>2</sup> direct and indirect deforestation for soybean expansion were characterized and quantified.

*Objective 3: To evaluate scale effects of regional land use dynamics in a coupled land use modeling setup.*

Understanding future land use and deforestation dynamics along the BR-163 will likely depend on land use change processes occurring at different scales. Combining a regional (Mato Grosso and Pará) and a subregional land use model for the selected BR-163 study region contributes to understand and better represent cross-scale land use change processes (Figure I-3). Two scenarios, a trend scenario and a sustainable development scenario were modeled, both defined and quantified within the project *Carbon Biodiversity and soCial structures* (CarBioCial, [www.carbiocial.de](http://www.carbiocial.de)).



#### 4 Overall structure of the thesis

This thesis consists of three core research chapters (chapter II, III, and IV) each advancing the above-mentioned research questions in accordance with the objectives. These core chapters are framed by the introduction (Chapter I) presenting the context and scientific background of the research chapters and the synthesis (Chapter V), which summarizes and discusses the main findings of the three research papers. Chapter II, III, and IV were written as standalone scientific articles, either published (II and IV) or submitted (III) to international peer-reviewed journals.

Chapter II **Gollnow, F., Lakes, T. (2014).** Policy change, land use, and agriculture: The case of soy production and cattle ranching in Brazil, 2001–2012. *Applied Geography*, 55, 203-211.

Chapter III **Gollnow, F., Hissa L.B.V, Rufin, P., Lakes, T. (submitted).** On property deforestation for soybean production in Mato Grosso, Brazil: investigating direct deforestation, on-property displacement, and property spillover deforestation. *Land Use Policy*.

Chapter IV **Gollnow, F., Göpel, J., Hissa, L.B.V., Schaldach, R., Lakes, T. (2017).** Scenarios of land use change in a deforestation corridor in the Brazilian Amazon: combining two scales of analysis. *Regional Environmental Change*.



Chapter II:  
**Policy change, land use, and agriculture: The case  
of soy production and cattle ranching in Brazil,  
2001-2012**

*Applied Geography, 2014, Volume 55, Pages 203–211*

Florian Gollnow, Tobia Lakes

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## **Abstract**

The Brazilian Amazon has experienced one of the world's highest deforestation rates in the last decades. Cattle ranching and soy expansion constitute the major drivers of deforestation, both through direct conversion and indirectly by land use displacement. However, deforestation rates decreased significantly after the implementation of the action plan to prevent and control deforestation in 2004. The aim of this study is to quantify the contribution of cattle and soy production with deforestation before and after the implementation of the action plan in the two states Mato Grosso and Pará along the BR-163. Specifically, we aim to empirically test for land use displacement processes from soy expansion in Mato Grosso to the deforestation frontier between 2001 and 2012. First, we calculated the relationships between deforestation rate and the change in cattle head and planted soy area respectively for the BR-163 region. Second, we estimated different panel regression models to test the association between processes of land use displacement. Our results indicate a close linkage between cattle ranching and deforestation along the BR-163 between 2001 and 2004. Soy expansion in Mato Grosso was significantly associated with deforestation during this period. However, these relations have diminished after the implementation of the action plan to control and prevent deforestation. With the decrease in deforestation rates in 2005, cattle ranching and deforestation were not directly linked, nor was soy expansion in Mato Grosso and deforestation at the forest frontier. Our analysis hence suggests that there was a close coupling of processes and spatial displacement until 2004 and a decoupling has taken place following the political interventions. These findings improve the understanding of land use displacement processes in Brazil and the methods offer potential for exploring similar processes in different regions of the world.

## 1 Introduction

The Brazilian Amazon has been subjected to one of the world's highest deforestation rates in the last decades (INPE, 2014a). Deforestation rates in the Legal Amazon increased from 2000 to 2004 from 18,226 km<sup>2</sup>/year to 27,772 km<sup>2</sup>/year respectively. Since then rates have been decreasing to 4,571 km<sup>2</sup>/year in 2012 (INPE, 2014a).

Understanding causes of deforestation and land use changes is crucial to curb deforestation. There are a large number of studies linking socio-economic and biophysical factors to deforestation in the Amazon region typically identifying drivers on municipal or grid level (Andersen and Reis, 1997; Pfaff, 1999; Laurance et al., 2002; Aguiar et al., 2007; Espindola et al., 2012). Most commonly, a combination of proximate and underlying causes have been identified as the main drivers of deforestation, i.e., cattle farming, road building, and accessibility to markets and ports (Margulis, 2004; Lambin and Geist, 2006). These drivers describe the local circumstances influencing deforestation. However, underlying causes on regional and global level may influence local drivers and put pressure on land conversions (Meyfroidt et al., 2013).

A couple of studies on regional and global drivers of deforestation in the Brazilian Amazon concentrate on the effects of global prices for agricultural goods, policy changes, and indirect land use change or land use displacement. Policy changes, especially the implementation of the action plan to prevent and control deforestation (PPCDAm, Plano de Ação para a Prevenção e o Controle do Desmatamento na Amazonia Legal) in 2004, had a significant effect on the decline of deforestation (Hargrave and Kis-Katos, 2011; Assunção et al., 2012; Assunção et al., 2013b). The PPCDAm focuses on three areas: first, territorial management and land use, e.g., expansion of the protected areas network (PPCDAm I 2004-2007); second, command and control, e.g., improved monitoring, licensing and enforcement of environmental laws (PPCDAm II 2008-2011) and third promotion of sustainable practices, e.g., by credit policies (PPCDAm III 2012-2015) (MMA, 2013). Additional campaigns include the soy moratorium agreed on in 2006 and the cattle moratorium agreed on in 2009. Both have shown promise in changing the patterns of deforestation (Rudorff et al., 2011; Rosa et al., 2012; Boucher et al., 2013).

Understanding processes of land use displacement or indirect land use change as an underlying driver of deforestation has gained special attention since the rapid expansion of export oriented agricultural production (Searchinger et al., 2008; Lapola et al., 2010a; Kim and Dale, 2011; Meyfroidt et al., 2013). In Brazil, this discussion mainly focuses on the

expansion of soybean and sugarcane production following the increased global and national demand for biofuel and animal fodder within the last decades (Morton et al., 2006; Andrade de Sá et al., 2013). This expansion led to the hypothesis of indirect land use change, i.e., the displacement of cattle ranching to the Amazon rainforest where it drives deforestation (Nepstad et al., 2006; Barona et al., 2010; Arima et al., 2011; Macedo et al., 2012; Richards, 2012b; Andrade de Sá et al., 2013).

Most studies on displacement processes in Brazil focus on the recent expansion of soy area, particularly on Mato Grosso (MT) as one of the world's most important production areas (DeFries et al., 2013). Morton et al. (2006) showed that soybean expansion most often replaced pasturelands. This conversion can be argued to be a process of intensification, since financial returns per area of land increased (Brandão et al., 2005). However, if the output of the replaced activity faces a relatively inelastic demand, as it is likely for stable food products like meat, the production will probably be reconstituted in another place where it can act as a local driver of land use change (Andrade de Sá et al., 2012; Andrade de Sá et al., 2013).

In detail, Nepstad et al. (2006) suspected that the expansion of the Brazilian soybean industry drove cattle expansion of the Amazonian cattle herd indirectly. Barona et al. (2010) concluded that the expansion of soy production might have operated as an underlying driver of deforestation displacing pasture further north into the forested areas, where pasture expansion is the predominant proximate cause of deforestation. Using a panel regression approach Arima et al. (2011) and Richards (2012b) found soy expansion in Brazil had a significant effect on deforestation in the Amazon forest between 2002 and 2008. However, analyzing the migration history of farmers and ranchers, Richards (2012b) could not clearly identify patterns of movement to support the idea of "spatial redistribution of knowledge and capital" from the soy expansion areas to the forest frontier.

This study aims to understand the coupling of cattle production and soy production with deforestation processes within the Amazon region along the BR-163. The BR-163 region has been one of the most dynamic forest frontier regions within the Brazilian Amazon connecting the soy production areas in Mato Grosso (MT) with the forested region in the north of MT and Pará (PA). We analyzed the local evolution of cattle and soy production in relation to deforestation, and the effect of distant soy expansion in Mato Grosso on deforestation at the forest frontier using a fixed effects panel regression. Different from earlier studies, we explicitly focus on the change in displacement processes before and after the implementation of the PPCDAm and aim for statistical evidence for displacement processes.

More specifically our research questions are:

- How does the coupling of land use processes, i.e., cattle and soy production with deforestation, change along the BR-163 between 2001 and 2012?
- Can we find statistical evidence of land use displacement from the soy expansion area in Mato Grosso as source region to the forest frontier areas in the Brazilian Amazon? How does land use displacement change following the implementations of the PPCDAm in 2004?

## **2 Material and methods**

### **2.1 Study region**

This study explores one of the hotspots of deforestation in the Brazilian Amazon: the region along the BR-163 traversing the Brazilian Amazon from Cuiaba, MT to Santarem, PA (INPE, 2014a). We selected those 31 municipalities that intersect with a 150km buffer along the road starting in the south with the Amazon Biome border and framed in the north with the Transamazonica road (Figure II-1). This area captures the most relevant frontier development following the construction of the highway in 1973 as an export corridor for agricultural productions in MT (Fearnside, 2007; Coy and Klingler, 2011).

The study region comprises 500,580 km<sup>2</sup> and is dominated by forest area (2001: 411,249 km<sup>2</sup>, 2012: 376,622km<sup>2</sup>), cattle ranching (2001: 4,245,462 heads, 2012: 7,436,330 heads), with an estimated stocking density of 0.009 animal per km<sup>2</sup> in 2006 and 0.01 animal per km<sup>2</sup> in 2013 (Martha et al., 2012; Walker et al., 2013), and soybean production (2001: 3,430 km<sup>2</sup>, 2012: 14,884 km<sup>2</sup>). Other livestock only constitute a minor share of total livestock population (Figure SI II-2). Soybeans as the main crop are increasingly planted in double cropping systems followed by maize, cotton or a non-commercial crop (Arvor et al., 2011b; Arvor et al., 2011a). Deforestation rates increased sharply between 2001 and 2004 from 3,995 km<sup>2</sup> to 6,431 km<sup>2</sup> and decreased until 2012 to 728 km<sup>2</sup> (INPE, 2014a).

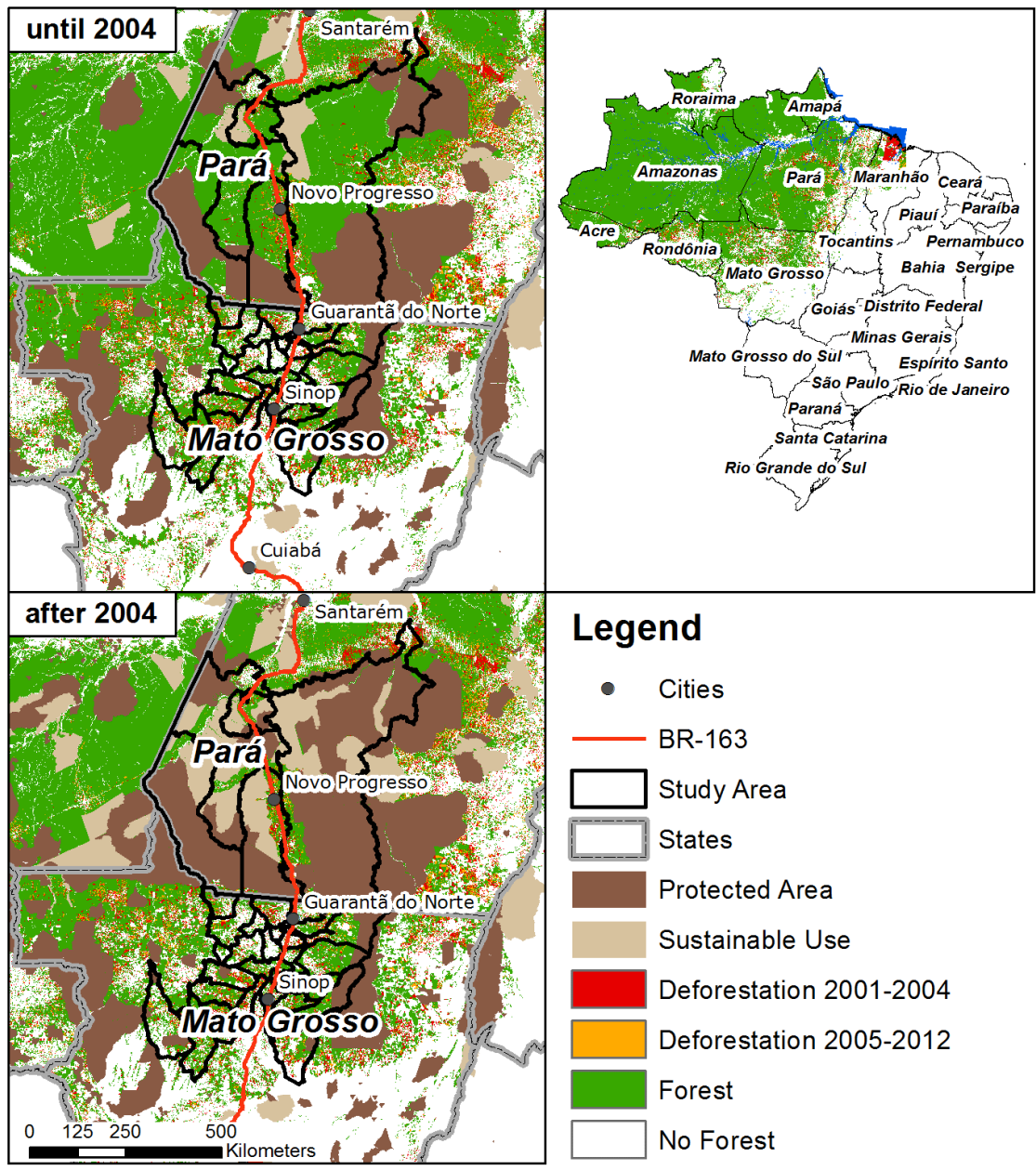


Figure II-1: Study region

Following the implementation of the PPCDAm in 2004, a number of protected areas, indigenous lands and sustainable use areas were expanded or created within the study region (Figure II-1). Additionally, command and control policies were enforced, e.g., the opening of an IBAMA (Brazil's federal environment protection agency) office in Novo Progresso in 2007, the identification of priority areas for law enforcement, and a rapid response program based on the 15 days DETER (Detecção de Desmatamento em Tempo Real) monitoring interval (Anderson et al., 2005; Assunção et al., 2013b; INPE, 2014b). In 2008, changes in public credit policies were implemented conditioning the concession of rural credit upon



compliance with legal and environmental regulations. This included, among others, legal property rights (Cadastro Ambiental Rural) and limited deforestation per municipality (Governo do Pará). These regulations especially affected those municipalities where cattle ranching is the predominant activity (Assunção et al., 2013a). Additionally, in 2006 the “soy moratorium” and in 2009 the “beef moratorium” were implemented. Both are agroindustry led initiatives with the objective to limit deforestation by direct encroachment of soy fields and pasture areas into forest (Boucher et al., 2011; Rudorff et al., 2011).

## 2.2 Data

Data on annual deforestation rates (km<sup>2</sup>) aggregated per municipality was acquired from PRODES/INPE for the years 2001 to 2012 (Instituto Nacional de Pesquisas Espaciais INPE, 2014a). Since 1988, INPE has been monitoring and improving their methodology to accurately map deforestation (Câmara et al., 2006; INPE, 2014a). PRODES deforestation estimates refer to the first of August of each year and account for gross deforestation with a minimum mapping unit of 6.25ha (Câmara et al., 2006). To assess cattle farming and soy production we used annual data on planted soy area in km<sup>2</sup> and annual heads of cattle per municipality in 1,000. Annual pasture area is – to the knowledge of the authors – unfortunately not available for 2001 to 2012. Both datasets were acquired from the municipal livestock and agricultural production survey available in the SIDRA-Database which provides one of the most detailed public available databases for Brazil on an annual basis (IBGE). Crop area estimates from the agricultural survey are counted separately for each crop rotation (Morton et al., 2006). The annual planted soy area describes the area demand of soy production independent of production increases or land use intensification based on increasing double cropping practices. From these datasets, we calculated the annual changes of cattle head and planted soy area (km<sup>2</sup>) per municipality.

## 2.3 Methods

First, we analyzed the relationship between the two main land uses, i.e., cattle and soy production change with deforestation rate, using deforestation transfer ratios. Second, we used fixed effects models to estimate the effect of distant soy expansion and local cattle expansion on deforestation (2.3.1). Model specification was built upon a selection of source and target municipalities of possible land use displacement. We used separate models to evaluate how land use displacement processes changed following the implementation of the

PPCDAm by comparing the period before the implementation (2001-2004) and afterwards (2008-2012) (2.3.2).

### ***2.3.1 Coupling between deforestation, cattle and soy production***

To analyze the linkages and dynamics of soy and cattle production in relation to deforestation processes we calculated an annual deforestation transfer ratio for the whole study region (Gasparri et al., 2013).

$$Deforestation\ Transfer\ Ratio_t = \sum_{i=1}^n Deforestation\ Rate_{it} / \sum_{i=1}^n Land\ Use\ Change_{it} \quad (1)$$

This deforestation transfer ratio quantifies the relationship between the summed deforestation rate (km<sup>2</sup>) over the municipalities  $i$  at year  $t$  and the respective land use change, i.e., summed change of cattle (1,000 heads) and summed change of planted soy area (km<sup>2</sup>) over  $i$  at year  $t$ . To account for the full time periods before and after the implementation of the PPCDAm we explicitly compared how the deforestation ratio changed between 2001 to 2004 and 2005 to 2012.

A deforestation transfer ratio of one, means that an area of one km<sup>2</sup> was deforested for 1,000 additional cattle head. For planted soy area change a value of one refers to one km<sup>2</sup> deforested area for one additional km<sup>2</sup> of soy area planted. Small values imply a decoupling of the two processes, for instance, land use increases, but deforestation rates do not equally respond to it. An intensification of cattle production (increase of stocking density) results in a decrease in the deforestation transfer ratio, because the decrease in area required for production reduces the need to clear new land by deforestation. In the case of soy area change, values around a one to one relation (1km<sup>2</sup> to 1km<sup>2</sup>) generally imply a coupled system where changes in land use are mirrored in changes in deforestation rates. Equally for cattle (change in 1,000 heads), a 10 to one ratio, considering an estimated stocking density of about 0.01 animals per km<sup>2</sup>, generally implies a coupled system. Larger values of the deforestation transfer ratio reflect an increase of deforestation without similar changes in the land use at hand. This suggests a minor direct contribution of the respective land use on deforestation.

### ***2.3.2 Panel regression model***

For the statistical analysis of land use displacement following soy expansion in MT and cattle ranching expansion at the forest frontier, we estimated fixed effects panel regressions. The model specification of land use displacement was built upon the definition of annual target and source municipalities. The target municipalities describe those municipalities

within our study region along the BR-163 in MT and PA where cattle population increased from one year to the other. From those target municipalities, we only included the ones where soy expansion was smaller than deforestation so as to omit municipalities where soy expansion drove deforestation directly. A minimum of 30% forest cover was set as a threshold to reduce the effect of decreasing likelihood of deforestation as forest cover declines (Richards, 2012b). The source region encompasses all municipalities in MT, which experienced soy expansion and are not defined as target municipalities. This reduced the analysis to those municipalities from where displacement of cattle could possibly take place because of soy expansion. It accounts for the spatial and temporal heterogeneity of potential land use displacement within the study region.

Deforestation rate in the target region was set as the response variable and total soy expansion in the source region as the explanatory variable. To account for the difference in size of the target municipalities in relation to soy expansion we introduced a weight matrix, defined as municipality area divided by the maximum municipality size, assuming that the amount of displacement is related to the municipality size. We also examined if changes in cattle population in the target regions correlated with deforestation to test the assumption that soy expansion displaced cattle and thereby induced deforestation.

The general fixed effects panel model is defined as:

$$y_{it} = \alpha_i + \beta' X_{it} + u_{it} \quad (2)$$

With the response variable at municipality  $i$  and time  $t$ , the individual intercept for each municipality, the slope of the estimation, the explanatory variable at time  $t$  in municipality  $i$ , respectively weighted by the municipality area and the error component. The fixed effects model accounts for time constant unobserved heterogeneity between the municipalities, such as soil suitability and differences in relief, which structurally favor one municipality over another (Croissant et al., 2008; Arima et al., 2011). The analysis was done with the `plm` package in R (Croissant et al., 2008; R Core Team, 2013).

To minimize the effect of the decrease in soy prices between 2005 and 2007 (Figure SI II-1) and to avoid the transition period following the implementation of the PPCDAm I to PPCDAm II, we designed the models for the years 2001 to 2004 and 2008 to 2012. Moreover, we focused on the separate association between deforestation rates and soy and cattle changes respectively. Thereby, we avoid problems of collinearity between the datasets in the model and are able to interpret the model results focused on the specific association. In total we calculated four models: A1 (2001-2004): Deforestation =  $f(\text{Weights} * \text{Soy}$

Expansion), B1 (2001-2004): Deforestation =  $f(\text{Cattle Expansion})$ , A2 (2008-2012): Deforestation =  $f(\text{Weights} * \text{Soy Expansion})$  and B2 (2008-2012): Deforestation =  $f(\text{Cattle Expansion})$ .

To obtain a more robust panel dataset, those municipalities with less than three observations were eventually omitted from the analysis. For the first period of four years, 21 target districts were identified with 3 to 4 observations over time; for the second period of 5 years, 13 target districts were identified with 3 to 5 observations over time. Finally, model fit was quantified by calculating the  $R^2$  value.

In line with earlier studies (Arima et al., 2011; Richards, 2012b; Andrade de Sá et al., 2013), we ran our models including a one year lag of soy expansion in the source region. The lagged model led to similar overall results but did not improve the explanation of land use displacement before the implementation of the PPCDAm (measure by  $R^2$ ). For the period after the implementation of the PPCDAm, both coefficients (lagged and non-lagged soy expansion) were negative and significant which underpins the results from the non-lagged model (Figure SI II-1).

### **3 Results**

#### **3.1 Coupling between deforestation, cattle and soy production**

We identified distinct changes in the processes of deforestation, soy and cattle production in the entire study region between 2001 and 2012.

Cattle population increased from 4.245 million heads in 2001 to 6.2 million heads in 2006, followed by a short decline to 5.67 million in 2007 (Figure II-2). Cattle population rapidly expanded again in 2008 surpassing the number of cattle present in 2006 (6.24 million heads) and increased to 7.53 million in 2011 before it declined slightly in 2012 (7.44 million heads). Soy area increased rapidly within the study region from 3,430 km<sup>2</sup> in 2001 to 10,365 km<sup>2</sup> in 2005. Similar to cattle, soy showed a short decline in area in 2007 to 8,082 km<sup>2</sup> but then strongly increased again to 14,884 km<sup>2</sup> in 2012.

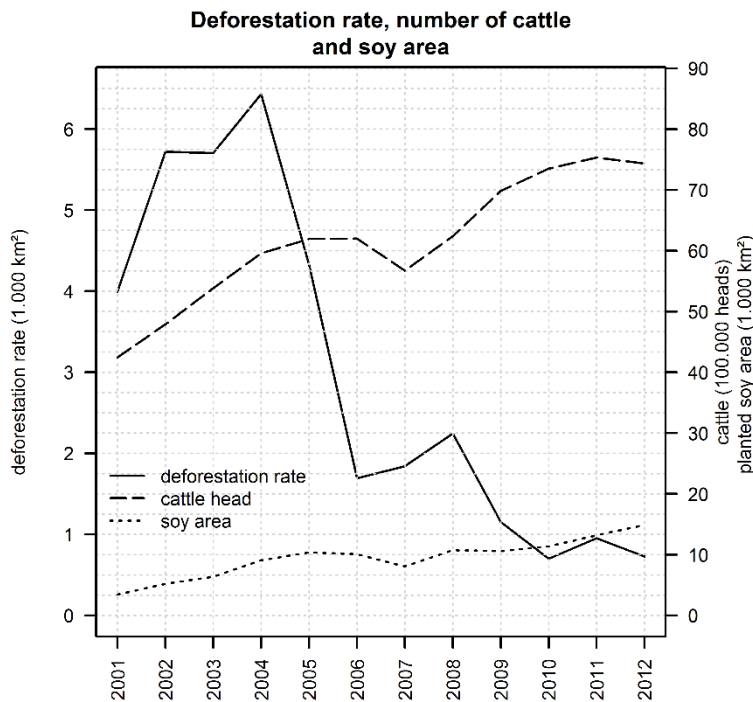


Figure II-2: Deforestation rate, number of cattle, and planted soy area

Between 2001 and 2004 the transfer ratio varied along a value of about 10 for deforestation rate and cattle change, which refers to an area of 10 km<sup>2</sup> deforestation for each additional 1,000 cattle per year (Figure II-3a). For 2005 and 2006 we received high values that show that more deforestation per increase of cattle occurred than before. Especially in 2006, the deforestation rate was largely independent from changes in the number of cattle. In 2007 we observed a negative transfer ratio, following the decline in the number of cattle within the study region, accompanied by dropping deforestation rates. The transfer ratio stabilized for the following four years at a value of about two. This refers to a deforestation area of about two km<sup>2</sup> for each additional 1,000 cattle. Associated with the decline in cattle population in 2012, the transfer ratio again showed negative values. The comparison between the aggregated period of 2001 to 2004 and 2005 to 2012 indicated a slight decline from 9.98 to 9.21.

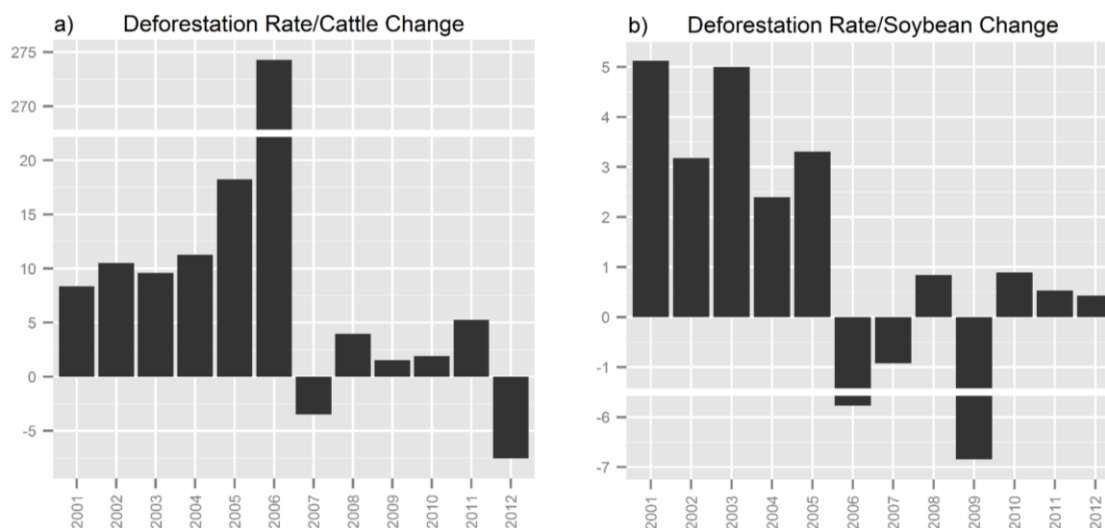


Figure II-3: a) Transfer ratio of changes in cattle (in 1,000 heads) and deforestation rate (in km<sup>2</sup>), b) Transfer ratio of soy area change (in km<sup>2</sup>) and deforestation rate (in km<sup>2</sup>)

The transfer ratio between deforestation rate and planted soy area change was far above a one to one relationship for the years 2001 to 2005 (Figure II-3b). Up to five times as much deforestation as soy expansion occurred. Planted soy area declined for the years 2006, 2007, and 2009. In 2008 and 2010 the transfer ratio of soy expansion stayed just below one and declined in the following years to 0.42. The aggregated transfer ratio declined from 3.40 (2001-2004) to 2.34 (2005-2012) showing that less area was deforested in relation to new soy area.

### 3.2 Panel regression model

Using the panel regression models, we estimated the displacement effects of soy expansion in MT on deforestation along the BR-163. To specifically focus on the process of displacement following soy expansion in MT displacing cattle production to the forest frontier, we defined a target region of cattle expansion in the study region and a source region where planted soy area expands in MT. The target municipalities point to the spatial-temporal development of the deforestation frontier where cattle expanded (Figure II-4). While cattle expansion was dominant for most of the study region in the first 5 years, cattle ranching eventually lost some of its importance in the south of the BR-163 region. From the 31 municipalities a maximum of 20 in 2001 and a minimum of 6 in 2012 were selected as target municipalities.

The number of source municipalities, i.e., from where displacement could possibly occur, steadily increased from 44 to 81 municipalities between 2001 and 2004 (Figure II-4). In 2008, 64 municipalities were identified as source region of possible displacement. In the following years, soy area again expanded in the other municipalities. In 2012, 72 municipalities in MT were defined as source region.

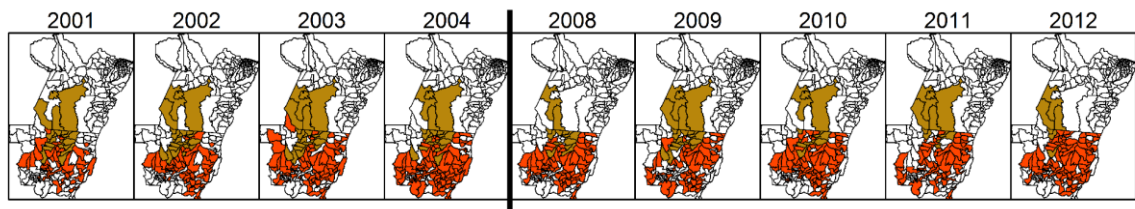


Figure II-4: Municipalities identified as target region (in brown) and source region (in red) from 2001 to 2012

For these two periods, we evaluated the weighted summed soy expansion in the source region as explanatory variable for deforestation in the target municipalities (Table II-1: A1, A2). In the following, we tested whether cattle expansion in the target region was a significant explanatory variable for deforestation (Table II-1: B1, B2), to verify the indirect link of soy expansion in MT and deforestation along the BR-163.

Model A1 and B1 describe the association for the pre-PPCDAm period from 2001 to 2004 (Table II-1). We identified a significant association between soy expansion in the source region and deforestation in the target municipalities (Table II-1: A1). Similarly, the increase of cattle was significantly associated with deforestation in the target municipalities for the first period (Table II-1: B1). Both models show a low but significant  $R^2$  of 0.08 and 0.07 respectively.

Model A2 and B2 describe the period between 2008 and 2012 following the implementation of the PPCDAm. Soy expansion returns a significant negative beta (Table II-1: A2), while cattle change in the target municipalities continues to be significant and positively associated with deforestation (Table II-1: B2). However, the effect of cattle ranching decreased by almost 50% compared to the period 2001 to 2004, while the  $R^2$  of the model increased threefold.

Table II-1: Fixed effects panel regression

Model	Time Period	Model Specification	$\beta$	R <sup>2</sup>
A1	2002-2004	$Deforestation Rate_{it} = f(W_i \sum_{i=1}^n \text{Soy expansion Source}_{it})$	0.05621*	0.088
B1	2002-2004	$Deforestation Rate_{it} = f(\text{Cattle change in 1,000 Target}_{it})$	0.88441*	0.077
A2	2008-2012	$Deforestation Rate_{it} = f(W_i \sum_{i=1}^n \text{Soy expansion Source}_{it})$	-0.05689.	0.098
B2	2008-2012	$Deforestation Rate_{it} = f(\text{Cattle change in 1,000 Target}_{it})$	0.49755* *	0.256

Model A1 & B1: Unbalanced Panel: n=21, T=3-4, N=74

Model A2 & B2: Unbalanced Panel: n=13, T=3-5, N=47

Significance levels: p < 0.1; \* p < 0.05; \*\* p < 0.01; \*\*\* p < 0.001

#### 4 Discussion

Our findings suggest important changes in the linkages between the three land use processes, soy expansion, cattle dynamics and deforestation along the BR-163 between 2001 and 2012.

The year of implementation of the PPCDAm was associated with a structural break in terms of land use. Before this, cattle changes were closely coupled with deforestation along the BR-163. This is indicated by a transfer ratio of about 10, which approximates the pasture area requirements considering the estimated stocking density for the Amazon of 0.009 animals per km<sup>2</sup> in 2006 and 0.01 animal per km<sup>2</sup> in 2013 (Martha et al., 2012; Walker et al., 2013). Cattle changes were therefore directly reflected in the amount of deforestation during the respective year. We hence assume that cattle increases were related to the expansion of pastures, rather than to the intensification of production system, i.e., an increase in stocking density, which would require less land. This is in line with earlier studies, which identified the BR-163 frontier region as an area of extensive cattle production (Bowman et al., 2012).

The years 2005 and 2006 were characterized by an increase of the deforestation transfer ratio. This divergence of deforestation rates and cattle change possibly indicates a process of structural inertia of the local adaptation to the new regulations (Hannan and Freeman, 1984). While the number of cattle declined in 2007, deforestation continued on a low level. This resulted in a surplus of cleared area, despite the decrease in deforestation rate.

Since 2008, the change in cattle population and deforestation appeared temporally decoupled. Cattle population increased, already surpassing the number of cattle in 2004 by



2008, but deforestation rates did not respond with a similar increase (Figure II-3a). From 2008 onwards, the transfer ratio of deforestation rate and cattle change stayed far below the ratio of the pre-PPCDAM period. Increased land constraints following the implementation of PPCDAM likely fostered a process of intensification of ranching activities on already cleared lands as observed in other regions of Brazil (Strassburg et al., 2014). This supports the finding of Assunção et al. (2012) who argues that if policy measures had not been implemented deforestation rates would have increased after the recovery of agricultural prices in 2007. However, the transfer ratios aggregated for the pre-PPCDAM period (2001-2004) and post-PPCDAM period (2005-2012) decreased only slightly. This indicates that the decoupling of cattle population and deforestation since 2008 can partly be attributed to deforested areas in 2006 and 2007. Those deforested areas in 2006 and 2007 likely provided pasture areas for the expansion of cattle ranching between 2008 and 2012.

As expected, soy expansion within the BR-163 region was not as closely linked to deforestation increases for the early 2000s. Deforestation rates by far exceeded the increase of soybean production in the area.

The decline in soy area in 2006 and 2007 was quickly regained in 2008, whereas we found a roughly stable amount of area used for soy production from 2008 to 2009. In 2008 and 2010, soy expansion stayed below the one to one ratio, which indicates an increased pressure on land due to the expansion of soy plantations within the BR-163 region because the expansion rate was larger than the deforestation rate.

Following the soy moratorium in 2006, most soy expansion was found to occur on already cleared lands (Macedo et al., 2012). Therefore, soy expansion can rather be viewed as an indirect driver of deforestation, expanding on pasture areas instead of encroaching into primary forest itself. The soy moratorium additionally inhibited large scale soy expansion to areas cleared after 2006 (Rudorff et al., 2011; Rudorff et al., 2012). However, the change in the public credit policy following the implementation of the PPCDAM might also have modified farmers' decision to change from cattle to soy production. Credits for soy production are not as dependent on the official rural credit system, where most of the financial requirements are met by the processing industry (Assunção et al., 2013a). Yet, during the decline of soy area in 2006, 2007, and 2009, and the decline in cattle heads in 2007 deforestation continued. This resulted in an addition of cleared areas, partly providing land for the later expansion. When comparing the aggregated transfer ratios for the period

2001 to 2004 and 2005 to 2012, the ratio declined from 3.40 to 2.34 km<sup>2</sup> area cleared for each km<sup>2</sup> of soy expansion.

Concerning the first research question, we can summarize that deforestation was closely coupled to cattle ranching until 2004. In 2005 to 2007 more area was deforested than actually needed in respect to changes in cattle population and soy production of the previous years. 2008 to 2012 can be interpreted as a temporal decoupling of cattle and soy production from deforestation. This can be understood as a combination of intensification processes and expansion on areas cleared in the previous years. Additionally, soy production gained importance in the region along the BR-163 compared to the early 2000s.

Moreover, our findings allow an empirical assessment of the land use displacement processes in the region. The definition of a target region explicitly considers the spatio-temporal heterogeneity of the study region taking into account the decrease of cattle production for some of the municipalities. The selection spatially describes the development of the cattle-deforestation system. In the south of the study area, cattle lost some of its importance during the period of analysis. Additionally in 2007, 2008, 2010, and 2012, some municipalities in PA dropped out of the frontier definition. Soy expansion in MT outside the target region expanded constantly until 2005, followed by a decrease of source municipalities until 2008. The decrease of municipalities selected as source municipalities follows the decline of the soybean prices (Figure SI II-1). In 2007, maize was partly used as a substitute for soybean (Reenberg and Fenger, 2011, see Figure SI II-3). This suggests that the following expansion was not as likely to displace cattle but to replace maize planted during the period of low prices.

Based on the selected municipalities of target and source regions our results of the fixed effects regression supported the hypotheses of indirect land use change for the pre-PPCDAM period. Methodologically, we deviated from a distance-weighted influence of the source region to the target municipalities as proposed by Arima et al. (2011) and Richards (2012b). Firstly, because our study focuses on regional displacement effects, and secondly because we would have difficulties arguing that within the displacement discourse the influence of a close place is higher than from a distant location.

The fixed effects regression indicated that soy expansion in the source municipalities had a significant effect on deforestation on the selected target municipalities for the 2001 to 2004 period. To underpin the indirect link between soy expansion and deforestation, we confirmed that cattle ranching in the target municipalities had a significant correlation with

deforestation. This result supports data driven evidence for earlier hypotheses of land use displacement (Nepstad et al., 2006; Barona et al., 2010) and is in accordance with findings from Arima et al. (2011) and Richards (2012b) who found soy expansion in the fringes of the Brazilian Amazon a driver of deforestation for the years 2001 to 2008. Different to the studies of Arima et al. (2011) and Richards (2012b), we partitioned our analysis before and after the implementation of the PPCDAm. The indirect link between soy expansion in MT with deforestation in the target municipalities could not be confirmed for the post-PPCDAm period 2008 to 2012. The effect of cattle ranching on deforestation decreased by almost 50% and the model fit ( $R^2$ ) increased to 0.26. This is in accordance with our earlier findings of cattle ranching decoupling from deforestation for the years 2008 to 2012. Most importantly, soy expansion in the source municipalities decoupled from the deforestation dynamics in the target municipalities for the 2008 to 2012 period. This means that land use displacement due to soybean expansion leading to deforestation cannot be understood as a continuous process since the beginning of the rapid expansion of soy production in MT.

To summarize, regarding the second research question, we found statistical evidence of land use displacement of soy expansion being associated with deforestation for the pre-PPCDAm period. Processes changed after the implementation of the PPCDAm. Soy expansion and deforestation were not significantly associated, while the impact of cattle ranching on deforestation declined.

Results are challenged by a number of limitations referring to the data quality, spatial extent, the temporal resolution, and model specification. We fully relied on the quality of PRODES/INPE deforestation estimates and IBGE annual survey data, which are the best available data sources for deforestation, planted soy area and cattle population. However, the data has some limitations and quality issues. The spatial extent of the study region did not capture all dynamics related to land use displacement at the Brazilian scale. Soybean expansion in Maranhão, Tocantins and Piauí might additionally lead to displacement processes linked to deforestation or the conversion of other ecosystems. While the temporal resolution of the analysis of yearly intervals captures the development of soybean expansion since it is an annual crop, it might not represent all dimensions of the multiannual life cycle of cattle. Moreover, model specification was limited due to the small number of observation. Even though these limitations challenged our findings, we provided new empirical insights into the spatial displacement process in the BR-163 region of the Brazilian Amazon.

## 5 Conclusion

Our findings suggest that the associations between cattle ranching, soy expansion and deforestation along the BR-163 have been affected by changes in land use policies and management following the implementation of the PPCDAm. While cattle ranching was closely associated with deforestation before the implementation of the PPCDAm, a temporal decoupling after 2004 was observed. Similarly, the transfer ratio of deforestation and soy expansion declined following the implementation of the PPCDAm.

Our empirical findings hence support earlier studies of land use displacement within the study region as identified by Arima et al. (2011) and Richards (2012b) for the pre-PPCDAm period. However, the post-PPCDAm period was not equally affected by displacement. This underpins the importance of temporal discontinuity of the processes, as changes in policy affect these dynamics and are of major importance to take into account. However, we do not claim that displacement effects will not occur in future.

During the transition period following the implementation of the PPCDAm in 2004 to 2007, even though deforestation rates declined strongly, more land was deforested than used for cattle or soy production within the region. If deforestation dynamics stay decoupled from the displacement processes in MT, cattle ranching and soy production along the BR-163 will depend largely on the effort taken to promote sustainable intensification and actions to stop deforestation. However, we identified initial changes of agricultural expansion processes along with current efforts to decrease deforestation. Possible future pathways to achieve a persistent reduction of deforestation include subsidies for semi-intensive cattle pasture systems or taxes on conventional cattle pasture production, and the expansion of technology transfer and training services (Cohn et al., 2014; Strassburg et al., 2014).

Future studies on the process of intensification versus expansion of agricultural production could provide additional information on changes in land use management at the forest frontier after the implementation of the PPCDAm. Spatial displacement analysis will gain in considering temporal dynamics. For Brazil, it is additionally useful to analyze the full crop rotation system rather than a single crop type only, to accommodate for the ongoing intensification processes due to double cropping systems (Arvor et al., 2011b; Arvor et al., 2011a). Plans to introduce palm oil plantation on a large scale in the Brazilian Amazon might move the displacement process to a new level, possibly displacing cattle production either further into the forest regions or to more distant places (Ramalho Filho et al., 2010). The recent increase of deforestation rates in the Brazilian Amazon bring into question whether

the current strategies against deforestation are sufficient to prevent future deforestation (INPE, 2014a).

### **Acknowledgements**

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Supplementary Information

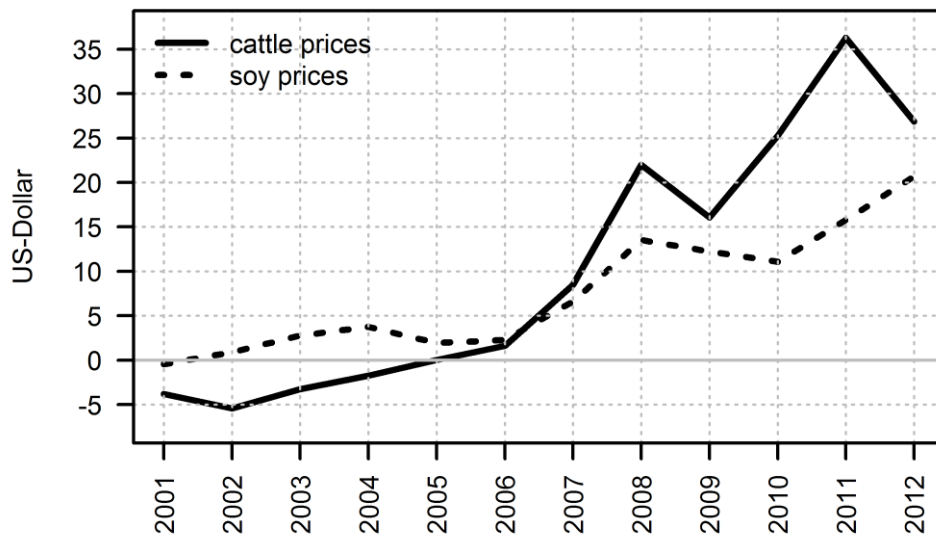


Figure SI II-1: Producer prices for cattle and soybean in price variation to the US-Dollar (exchange rates 2000). Source: SEAB-PR ([www.agricultura.pr.gov.br](http://www.agricultura.pr.gov.br)) and World Bank (<http://data.worldbank.org/indicator/PA.NUS.FCRF>).

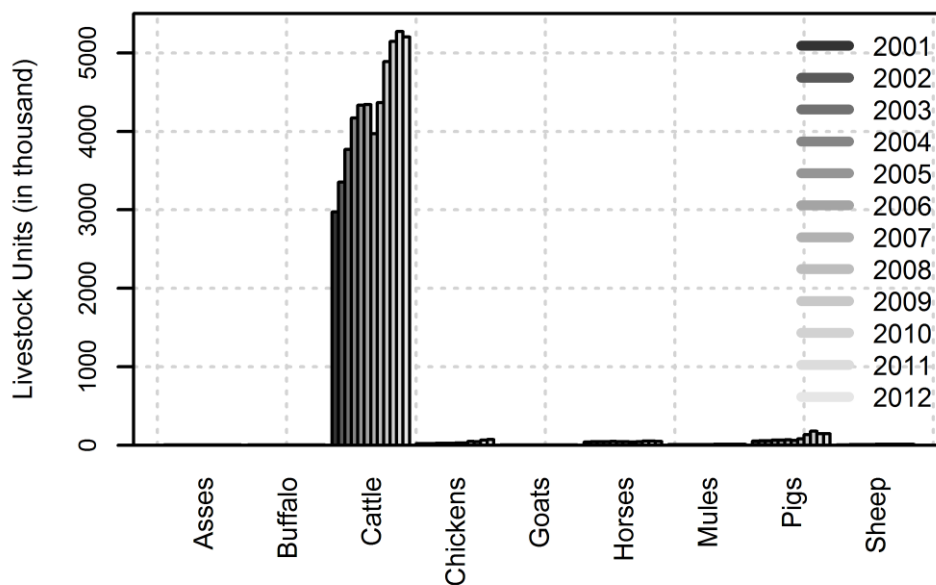


Figure SI II-2: Main livestock within the study region along the BR-163 in equivalent livestock units (Data: Pesquisa Pecuária Municipal (Table 73) (IBGE), Conversion factors see Chilonda and Otte (2006))

Table SI II-1: Lagged Models

Model	Time period	Model Specification	$\beta$
A1	2002-2004	$W_i \sum_{i=1}^n \text{Soy expansion Source}_{it}$	0.044475
		$W_i \sum_{i=1}^n \text{Soy expansion Source}_{i(t-1)}$	0.015465
		Adj. R <sup>2</sup>	0.073
A2	2008-2012	$W_i \sum_{i=1}^n \text{Soy expansion Source}_{it}$	-0.119202***
		$W_i \sum_{i=1}^n \text{Soy expansion Source}_{i(t-1)}$	-0.060771**
		Adj. R <sup>2</sup>	0.241

Model A1 & B1: Unbalanced Panel: n=21, T=3-4, N=74  
 Model A2 & B2: Unbalanced Panel: n=13, T=3-5, N=47  
 Significance levels: . p < 0.1; \* p < 0.05; \*\* p < 0.01; \*\*\* p < 0.001

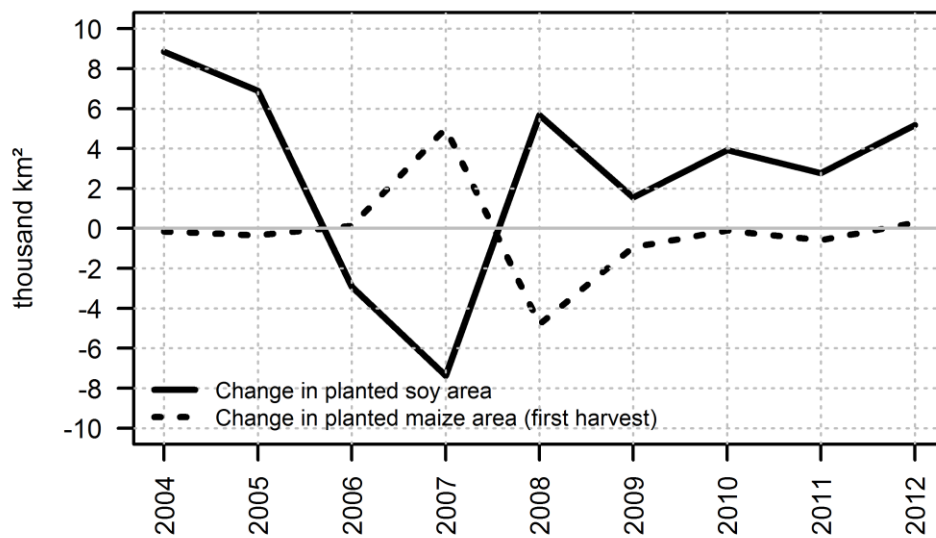


Figure SI II-3: Changes in planted soy area and planted maize (first harvest). Source: IBGE (agricultural production survey)





Chapter III:  
**On property deforestation for soybean production  
in Mato Grosso, Brazil: investigating *direct*  
deforestation, *on-property displacement*, and  
*property spillover* deforestation**  
*Land Use Policy (submitted)*

Florian Gollnow, Leticia de Barros Viana Hissa, Philippe Rufin, Tobia  
Lakes

*Submitted: 01.06.2017*

## **Abstract**

Brazil's Soy Moratorium sealed the commitment of the largest traders to stop soybean purchases from production areas deforested after July 2006. The aim was to ban deforestation from the grain's supply chain and halt one of the main drivers of forest losses in the Amazon biome. In this paper, we investigated changes in deforestation patterns to understand direct deforestation and indirect deforestation for soybean expansion at property scale in the Amazon region of Mato Grosso, the leading soy-producing state of the Brazilian Amazon. We used publicly available data on private properties and land use between 2004 and 2014 to quantify deforestation associated with soybean expansion. We found that deforestation for soybean doubled when we included indirect deforestation, caused by the displacement of pastures between 2012 and 2014. Increasing indirect deforestation coinciding with increasing prices for soybean challenges the effectiveness of the Moratorium. Most deforestation occurred on large land-holdings, which also host most of the private forest reserves. Even though these actors contributed the largest share of the decrease in deforestation in the past decade, they continue to be the main actors in deforestation for soybean. Our findings suggest that better control and reduction of future deforestation demand accounting for the interactions between crop and cattle production. This can be achieved by integrating efforts between supply chain actors, the soybean and beef purchasing companies, and the policies aiming to control deforestation.

## 1 Introduction

Following the rampant rates of forest losses dominating the early 2000s, Brazil has significantly reduced deforestation in the Amazon since 2005. Annual rates of deforestation dropped from more than 2.7 million hectares in 2004 to about 450 thousand hectares in 2012 (INPE 2017). This reduction was explained by a combination of environmental policies, supply chain interventions to ban deforestation from production, and decreasing prices for agricultural commodities (Hargrave and Kis-Katos, 2011; Assunção et al., 2015). Key policies were pooled under the Action Plan to Prevent and Control Deforestation in the Legal Amazon (PPCDAm) implemented in 2004, including territorial management, increased law enforcement and strategic allotment of rural credits (Assunção et al., 2015; MMA, 2016). Supply chain commitments among the major purchasing companies in Brazil banned soybean (i.e. the Soy Moratorium, agreed on in 2006) and beef (i.e. the MPF-TAC and G4 Agreement, signed in 2009) produced on newly deforested areas from the supply chain (Nepstad et al., 2014; Gibbs et al., 2015; Gibbs et al., 2016). These policies particularly affected large properties, which contributed the largest shares in deforestation (Godar et al., 2014). Following the implementation of the PPCDAm and the Soy Moratorium, overall deforestation decreased, mainly due to a decline in deforestation on large properties, while the deforestation on small properties did not decrease similarly (Godar et al., 2014). The resulting discussions on the implications and effectiveness of future policies suggested to either revise past policies towards actor balanced strategies, or to continue targeting large properties as those host large amounts of the remaining forest. This is particularly relevant in the light of increasing global demands of agricultural commodities which may trigger future deforestation (Godar et al., 2014; Richards and VanWey, 2015).

One of the most active deforestation and agricultural expansion frontiers in the Amazon is located in the federal state of Mato Grosso, ranking second on accumulated deforestation in the Brazilian Amazon (Arvor et al., 2016; INPE, 2017). Mato Grosso is a major soybean producing state in Brazil, the world's second-largest soybean-producing nation (FAO, 2017). Mato Grosso's land tenure structure is dominated by large properties, with 75% of the agricultural and ranch areas located on properties greater than one thousand hectares (Richards and VanWey, 2015). Following the large-scale expansion of soybean production in the early 2000s, causing extensive deforestation to open new areas for crop cultivation in the Amazon biome of Mato Grosso, non-governmental institutions raised concerns about the environmental impacts of production (Greenpeace, 2006). Consequently, Brazil's major

soybean trading companies agreed not to purchase soybeans produced on newly deforested areas, the Soy Moratorium, excluding production sites deforested after June 2006 (with the renewal of the agreement in 2014 the date was changed to June 2008) (Gibbs et al., 2015). Since then, direct deforestation for soybeans decreased (Rudorff et al., 2011; Macedo et al., 2012; Imaflora, 2016), while the share of deforestation for pasture increased (Macedo et al., 2012). However, increasing rates of deforestation since 2013 triggered new doubts about the effectiveness of the supply chain intervention and environmental policies.

Displacement and loopholes may have undermined the effectiveness of the Soy Moratorium and increased the environmental impacts of soybean expansion. Gibbs et al. (2015) and Rausch and Gibbs (2016) identified two possible loopholes, through which non-compliant soybean produce may have entered the supply chain. First, farmers often own or rent multiple properties, but, upon sale present the certification for one compliant property only. Production on the other properties may not be free from deforestation (Gibbs et al., 2015; Rausch and Gibbs, 2016). Secondly, soybeans produced on properties embargoed for illegal deforestation under current legislation (Lei de Crimes Ambientais, 1998; Código Florestal, 2012), have not been banned from the supply chain until the 2016 renewal of the Moratorium (Gibbs et al., 2015).

Land use displacements associated with the soybean production in Mato Grosso were discussed in different contexts. First concerns arose with the large-scale expansion in the early 2000s when pastures were often converted for soybean cultivation. Empirical linkages suggested a significant impact of distant soybean expansion driving deforestation in the inner Amazon (Arima et al., 2011; Gollnow and Lakes, 2014; Richards et al., 2014). In response to the implementation of the policies pooled under the PPCDAm and the Soy Moratorium, new displacement processes were anticipated. Specifically, concerns about cross-biome leakage, describing the displacement of land uses in response to the implementation land use restrictions (Meyfroidt et al., 2013) emerged. Considering the limitations of further expansion of soybean production in the Amazon regions, expansion might have been displaced to the Cerrado biome. Although Macedo et al. (2012) rejected the hypothesis of soybean leakage affecting deforestation in the Cerrado, recent research indicated a substantial expansion and deforestation for croplands between 2003 and 2013, concentrated in the Matopiba region, in the northern Cerrado (Noojipady et al. 2017). Three quarters of this expansion occurred at the expenses of native vegetation (Spera et al., 2014), which

partially offset the avoided emissions from deforestation in the Amazon (Noojipady et al., 2017).

Potential displacements effects were identified by Rausch and Gibbs (2016) describing a process of on-property leakage. Triggered by the implementation of the Soy Moratorium, they hypothesized that farmers decide to expand the area dedicated for soybeans by converting pastures to expand their soy areas and to deforest for cattle ranching instead. This would leave the farmer compliant with the Soy Moratorium while expanding their area of production.

In this study, we contribute to discussions on on-property leakage effects and the involvement of different property sizes to deforestation for soybean expansion. The complex interactions between soybean and cattle ranching affecting deforestation may result in considerable underestimation of soybean-driven deforestation. While previous research on land use displacement has focused on regional processes, there is a lack of studies exploring local processes of land use change and displacement at property level. We address this gap combining spatially explicit data on property boundaries (SICAR, 2017) and ten years of land use and cover maps (2004-2012) (INPE, 2015).

Specifically, we aim to quantify direct deforestation for soybean and conceptualize and quantify local processes of displacement at property scale in the Amazon biome of Mato Grosso. We used the term *on-property displacement*, to describe the sequential advance of deforestation for pasture following the advance of soybean expansion over pastures. To address the agriculture property structure, where one farmer may own or rent multiple properties (Gibbs et al., 2015; Richards and VanWey, 2015; Rausch and Gibbs, 2016), we defined and quantified *property-spillover* deforestation investigating displacement processes among neighboring properties. We stratified the findings according to property sizes and discussed deforestation rates by size classes. Specifically, we aim to analyze the following questions:

- How much on property deforestation for soybean production (direct deforestation, on-property displacement deforestation, and property spillover deforestation) occurred in the Amazon biome of Mato Grosso between 2004 and 2014?
- Which actors, represented by property size, contributed to deforestation between 2004 and 2014?

## 2 Methods

### 2.1 Study region

The study region comprises the area of the federal state of Mato Grosso that belongs to the Amazon biome (Figure III-1). Extensive cattle ranching with low stocking densities has been the characteristic land use, before large-scale agricultural expanded into the region (Hecht, 1993; Nepstad et al., 2006). Advances in the adaptation of soybean varieties overcame previous constraints on tropical production, related to the acidic, aluminum-rich soils and short photoperiods in the Amazon (Spehar, 1995; Spera et al., 2014). Between 2001 and 2007, soybean area in the Amazon region of Mato Grosso more than doubled from 0.88 to 1.96 million hectares (Arvor et al., 2011b). Next to expansion, increasing crop production was achieved by yield increases and the adoption of double cropping systems (Macedo et al., 2012; Spera et al., 2014). While total cropland area throughout Mato Grosso state increased by 75% from 3.3 to 5.8 million hectares between 2001 and 2011, the amount of double-cropped land increased six-fold, from 0.5 to 2.9 million hectares. Soybean-corn rotation accounted for 92% of double-cropped land in 2011 (Spera et al., 2014). Almost all crop fields in the Amazon region of Mato Grosso were dedicated to soybeans production, with soybean cultivated on 94.8% in 2001 and 97.3% in 2007 of all croplands (Arvor et al., 2011b). Following these findings, we assumed soybean expansion to be the dominant force underlying cropland expansion in the study region. Cropland expansion for soy cultivation mostly occurred by converting pastures. Between 2001 and 2005, 74% of cropland expansion occurred over pastures and 26% of the expansion occurred over forest (Macedo et al., 2012). Following the Soy Moratorium, deforestation for cropland expansion fell to 2% in 2010 (Macedo et al., 2012).

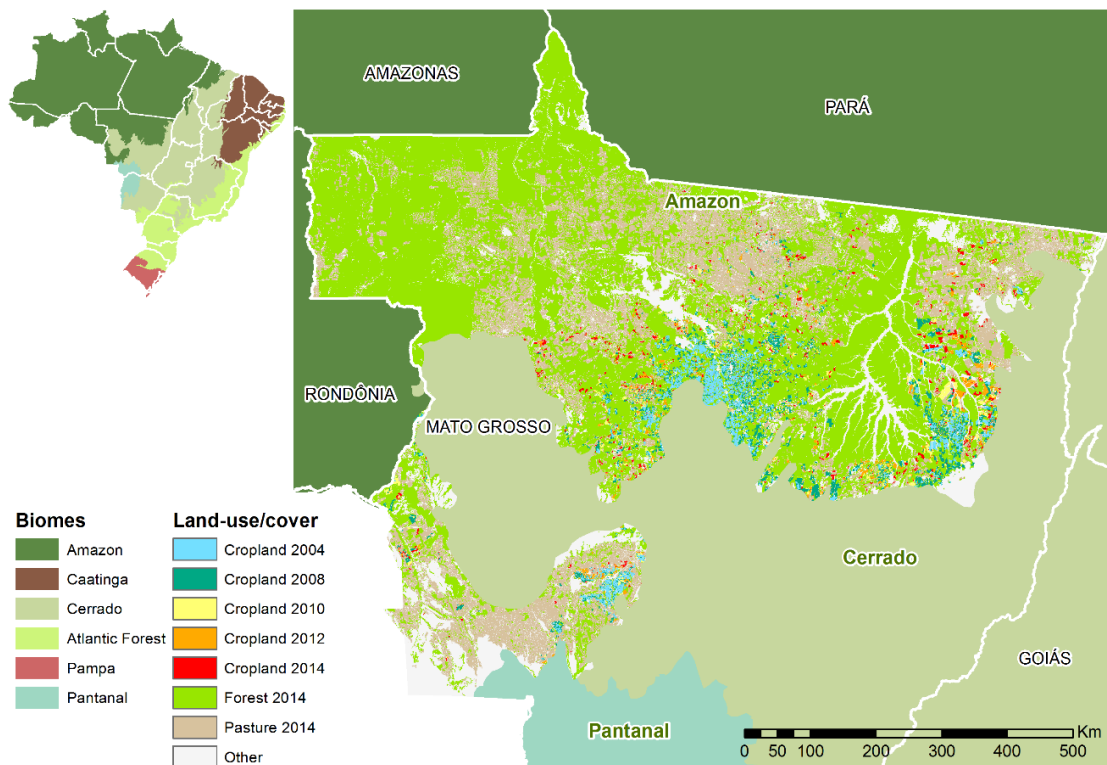


Figure III-1: Cropland expansion between 2004 and 2014 in the Amazon region of Mato Grosso (Source: INPE, 2015; MMA, 2015)

## 2.2 Data and Pre-processing

We used the TerraClass land use and cover product, provided by the National Institute for Space Research (INPE), covering the Brazilian Amazon biome for the years 2004, 2008, 2010, 2012 and 2014. The classification procedure aimed for consistency between years and class semantics, to allow a mapping of land use trajectories (INPE, 2015; Almeida et al., 2016). The TerraClass maps provide post-deforestation land uses based on the annual gross forest loss maps made available by the Brazilian Deforestation Monitoring Program (PRODES) (INPE, 2018). Relevant land uses for our analysis included croplands (Portuguese class: *agricultura annual*), used to approximate soybean cultivation, four pasture categories, referring to different vegetation covers (Portuguese classes: *pasto com solo exposto*, *pasto limpo*, *pasto sujo* and *regeneração com pasto*), forest (Portuguese class: *floresta*) and deforestation (Portuguese class: *desflorestamento*) that occurred within the reference year. The overall accuracy of TerraClass 2008 was estimated to be 89.7% for the entire Amazon biome (when pasture classes are merged into one class). The minimum mapping unit (MMU) of TerraClass is 6.25 hectares, derived from 30×30m<sup>2</sup> Landsat satellite

images (Almeida et al., 2016). Accounting for the MMU, we set a minimum conversion threshold of 6.25 hectares for all our analyses.

We obtained the information on private rural properties from the CAR public database (SICAR 2017). The CAR registry system was institutionalized as an instrument for the Brazilian Forest Code implementation and enforcement in 2012, and is intended to be used to support zero deforestation policies, promote conservation and natural resources valuation (Código Florestal, 2012). The property registry within the system is compulsory to all landholders until December 2017 (Lei N. 13.295/ 2016), however, at this stage, there are no impediments to the inclusion of false or conflicting information (e.g. overlapping properties, double cadastre).

We, therefore, identified and corrected spatial inconsistencies of overlapping boundaries of multiple properties in the CAR dataset (Figure III-2). This involved the change of boundaries or removal of properties in favor for spatial and geometric consistency. The final dataset comprised 48,282 properties covering an area of 25.2 million hectares, which represents 52.3% of the total area of the Amazon region of Mato Grosso. We classified these in five categories according to their size, following Richards et al. (2015) methodology: *micro*, properties < 100 Ha (27,306 properties); *small*, properties 100 < 250 Ha (8,528 properties); *medium*, properties 250 < 1,000 Ha (7,043 properties); *large*, properties 1,000 < 5,000 Ha (4,608 properties); *mega*, properties > 5,000 Ha (797 properties).

The CAR and TerraClass land use and cover datasets were projected and aligned to Albers Equal Conic (ESRI: 102033) projection with a 30x30m<sup>2</sup> resolution.

### 2.3 Analysis

We conceptualized *direct deforestation*, *on-property displacement* and *property spillover* deforestation as depicted in Figure III-2. *Direct* deforestation for soybean describes the conversion from forest or deforested areas to cropland.

We defined *on-property displacement* to be present when croplands expands over pasture while the area lost for cattle ranching was restored by clearing forest for pasture on the same property (conversion from forest or deforestation to pasture). The necessary conditions for *on-property displacement* were: (a1) Conversion from pasture to cropland; (a2) deforestation for pasture to restore the ranching area needed to support the same cattle herd.

As discussed earlier, spillover may occur when multiple properties are owned or rented by the same farmer. Since ownership information was not included in the CAR dataset available



to the public, we used a neighborhood criterion. We defined *property spillover*, to describe land use conversions within properties in relation to conversions in the adjacent properties. Adjacent properties were defined as those properties, which share the same boundary, considering a maximum snapping distance of 200m. This accounts for spatial inaccuracies of the CAR data. We defined *property spillover* to occur under the following three conditions: (b1) croplands expands over pastures within one property; (b2) the loss of pasture area needed to support the same cattle herd was restored within the adjacent properties through deforestation (including pasture to cropland conversion in the neighboring properties); (b3) the target property does not classify for *on-property displacement*.

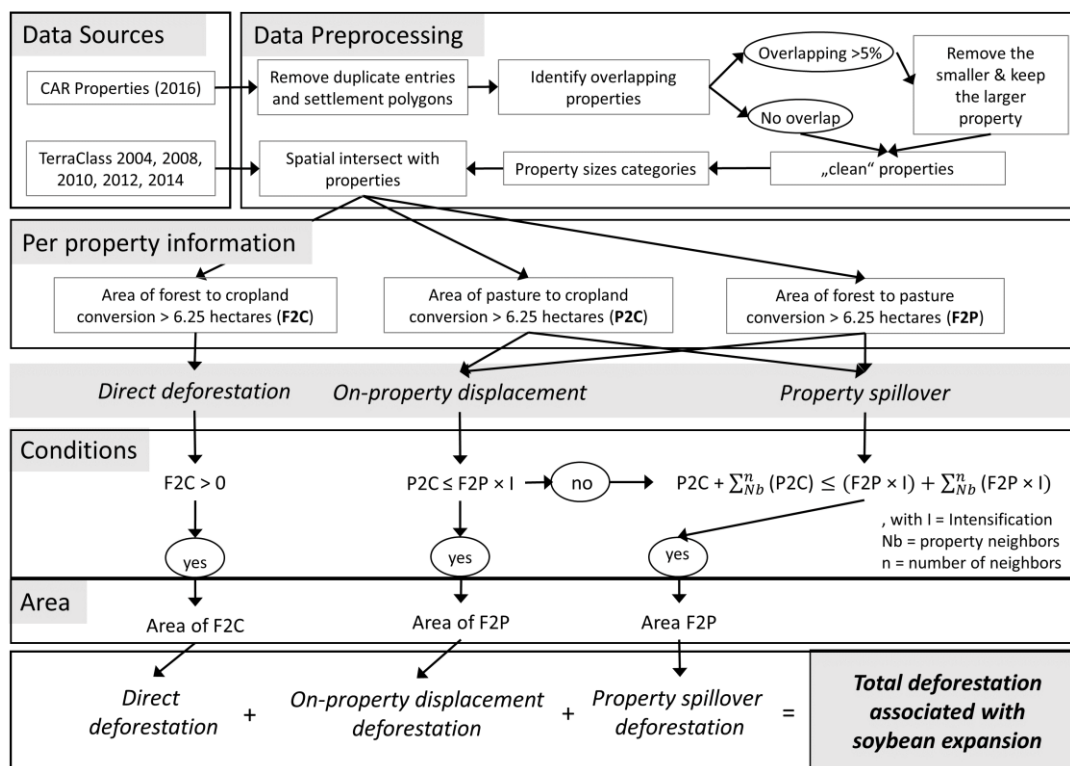


Figure III-2: Workflow identifying and quantifying direct deforestation, on-property displacement and property spillover deforestation related to cropland expansion

The decision of a farmer to expand their area of soy cultivation over pasture might be accompanied by efforts to increase the productivity of cattle ranching. For example, Cohn et al. (2014) and Walker et al. (2013) assume potentials for cattle ranching intensification around a factor of 2 to 2.5, following the best practices guide provided by the Brazilian Agricultural Research Corporation (Valle, 2007). We accounted for four different scenarios of cattle ranching intensification. According to the factor of intensification, the area required

to support the same herd size changes (the higher the intensification factor, the smaller the required areas - relevant for condition *a2* and *b2*). The factor 1 (I1) described no intensification, intensification by a factor of 1.5 (I1.5) accounted for moderate intensification, intensification by a factor of 2 (I2) assumed strong intensification and intensification by a factor of 2.5 (I2.5) referred to the maximum intensification. An intensification by a factor of 1.5, was assumed likely to be achieved. This would either allow more cattle on the same areas of land, increased by a factor of 1.5, or the same amount of livestock could be ranched on a smaller area, reduced by the factor 1.5.

### 3 Results

We identified an increasing number of properties cultivating crops between 2004 and 2014. In 2004 6% (3,070) and 2014, 13% (6,048) of the properties in our database (n: 48,282) had at least 6.25 hectares of areas dedicated to crops. These properties host about 25% (2014) or 3 million hectares, of the remaining forest inside private properties. About 55% of this forest (about 1.7 million hectares) was located within mega properties, 35% (1.1 million hectares) in the large properties and the remaining forest in the micro to medium properties (Table SI III-1). However, not all properties have forests left within their boundaries. From the 6,048 properties cultivating crop in 2014, we found that 1,662 (32%) properties had no forest cover larger than 6.25 hectares (MMU). Besides the increase in the number of properties dedicated to soybean production, the cultivated area on those properties more than doubled, expanding from 0.9 to 2.2 million hectares. Especially large and mega properties increased their share on the overall area of dedicated to soybean production. In 2014, we identified about 1.6 million hectares, or 70% of the soybean areas, within those two categories (Table SI III-2).

#### 3.1 Direct deforestation

On-property deforestation for soybean expansion decreased throughout our observation period. We found an average of 225 thousand hectares deforested each year between 2004 and 2008 compared to only 3 thousand hectares between 2012 and 2014 (Figure III-3; Table III-1). This observation period (2004 to 2008) combined pre- and post-Soy Moratorium observation and was the longest observation period of our analysis. *Direct* deforestation during those years was predominantly located within large and mega properties. These large and mega properties contributed largely to the reduction of deforestation for cropland of the following years. However, they continue to be responsible for the largest share of direct

deforestation for croplands in Mato Grosso, contributing with around 60% of the observed deforestation between 2012 and 2014 (Figure III-3).

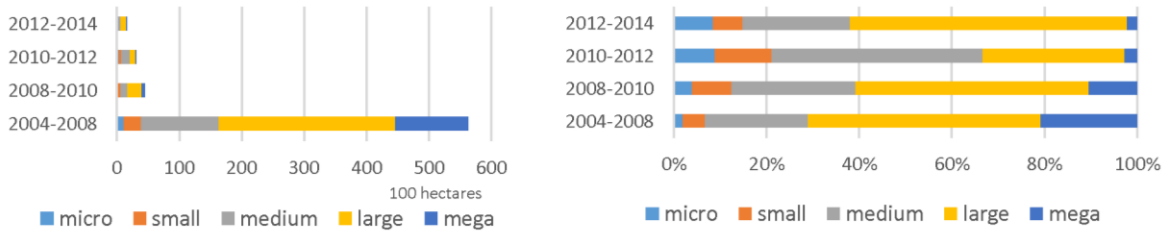
We found similar trends in the number of properties contributing to *direct* deforestation. Between 2004 and 2008, we observed 1,623 properties deforesting for cropland. The number of properties deforesting decreased in the following years to 164, between 2008 and 2010, and to 67 between 2012 and 2014. Most properties contributing to direct deforestation were either large or medium size (Table III-1).

### **3.2 On-property displacement deforestation**

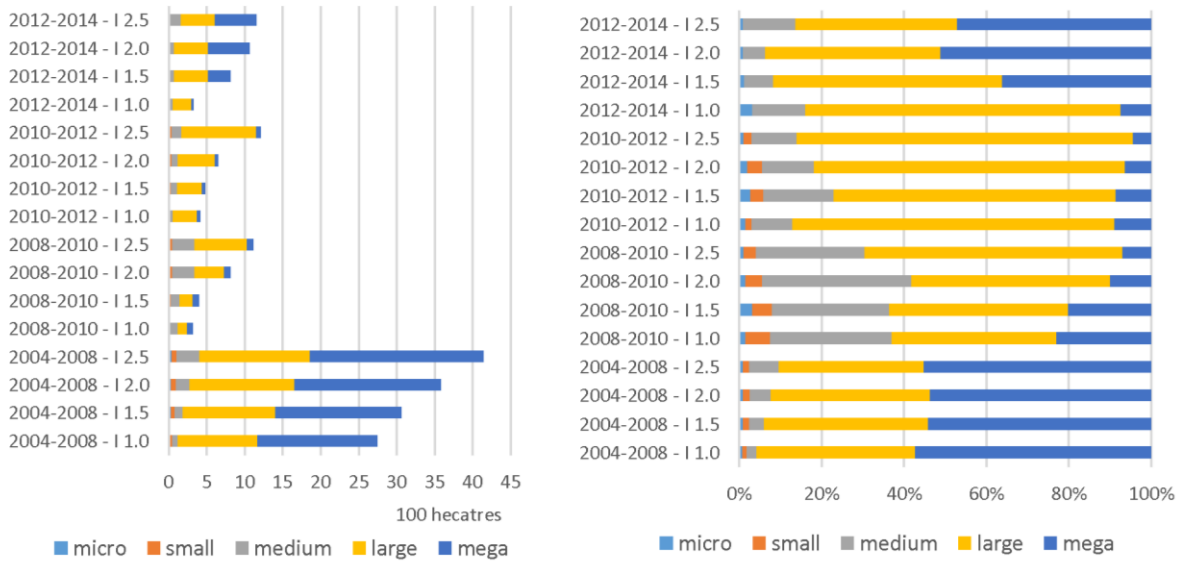
Properties expanding their area of soybean cultivation, often, simultaneously deforested for pastures. In line with the reduction of deforestation for soybean, annual deforestation for pastures decreased similarly. Deforestation for pasture added up to 22.18 thousand hectares per year between 2004 and 2008 and fell to about 3.96 thousand hectares per year for 2012 to 2014. 70% of deforestation for pasture between 2012 and 2014 occurred in the large and mega properties (Figure SI III-1).

We explored *on-property displacement* under different scenarios of cattle ranching intensification. Required pasture area conversions to sustain the same herd size thus varied according to the intensification factors. For the period between 2004 and 2008, we identified 116 (I1), 136 (I1.5), 156 (I2) and 175 (I2.5) properties falling under our definition of *on-property displacement*. These contributed between 2.7 thousand to 8.3 thousand hectares of annual deforestation associated with soybean expansion, depending upon the factor of cattle ranching intensification (Table III-1). In accordance with the overall decrease of deforestation, *on-property displacement* deforestation decreased throughout 2008 to 2012. Within the 2012 to 2014 observation period, we identified increasing *on-property displacement* deforestation under the medium (I1.5) and strong (I2.0) intensification scenario.

Mean annual *direct* deforestation for soybean production



Mean annual *on-property displacement* deforestation for soybean production



Mean annual *property spillover* deforestation for soybean production

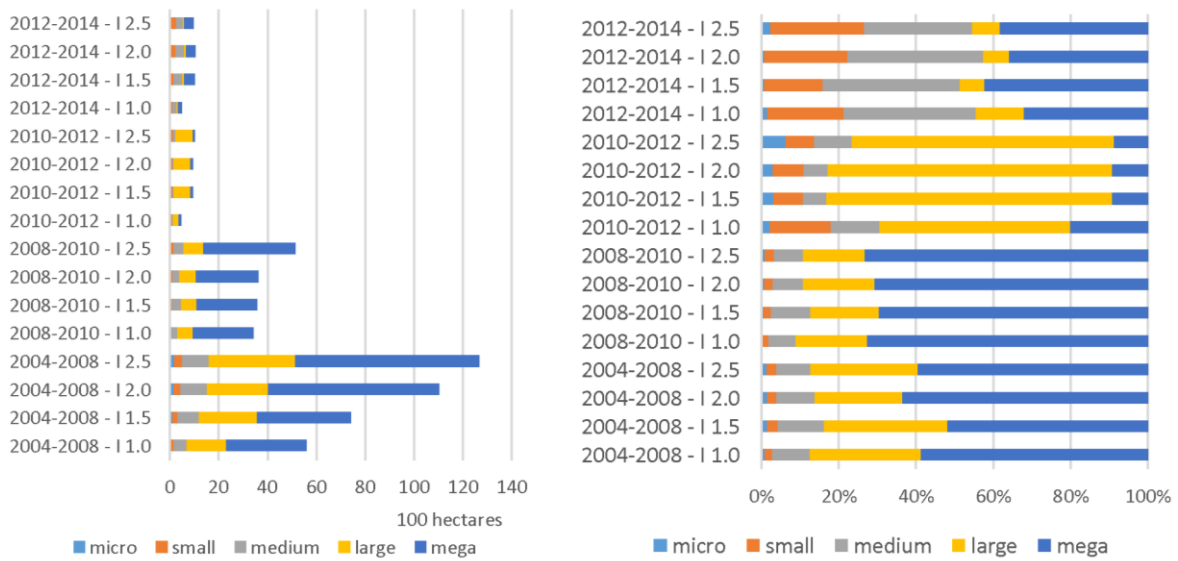


Figure III-3: Amount and distribution among property categories of direct

### 3.3 Property spillover deforestation

*Property spillover* deforestation related the expansion of croplands over pasture, to conversions from forest to pasture within the neighboring properties. We found that *property spillover* deforestation decreased during our observation period, similarly to the reduction of *direct* deforestation (Figure III-3). While *property spillover* added 5.6 to 12.7 thousand hectares of annual deforestation between 2004 and 2008, associated deforestation fell in 2010-2012 to 0.5-1 thousand hectares, according to the factor of intensification. While in 2012-2014 the amount of *property spillover* remained similar to the preceding period, the contribution among the property sizes changed. We observed a transition from large properties associated with *property spillover* deforestation towards increasing shares of small, medium properties on the one hand and mega properties on the other hand.

### 3.4 Total deforestation for croplands

Assuming a moderate intensification of cattle ranching (I1.5), we estimated, for 2012-2014 that *on-property displacement* together with *property spillover* deforestation more than doubles the amount of *direct* deforestation for croplands (Table III-1; Figure III-3). While direct deforestation for soybean production decreased throughout our analysis period, *on-property displacement* and *property spillover* increased in the last observation period (I1.5) (Table III-1; Figure III-3). Figure III-4 exemplarily shows the spatial distribution of *on-property displacement*, *property spillover* and *direct* deforestation in the Amazon region of Mato Grosso between 2012 and 2014.

Table III-1: Direct, on-property displacement, and property spillover deforestation associated with soy expansion

YEAR	ANNUAL DIRECT DEFORESTATION IN HECTARES	ANNUAL ON-PROPERTY DISPLACEMENT DEFORESTATION IN HECTARES				ANNUAL PROPERTY SPILLOVER DEFORESTATION IN HECTARES				TOTAL DEFORESTATION (I1.5) IN HECTARES
		I1	I1.5	I2	I2.5	I1	I1.5	I2	I2.5	
2004 - 2008	56,276 (1,623)	2,744 (116)	3,062 (136)	3,578 (156)	4,139 (175)	5,591 (132)	7,400 (186)	11,015 (218)	12,679 (248)	66,738
2008 - 2010	4,419 (164)	317 (29)	397 (36)	807 (43)	1,109 (46)	3,416 (41)	3,565 (44)	3,628 (55)	5,131 (69)	8,381
2010 - 2012	3,080 (132)	408 (10)	478 (17)	648 (20)	1,204 (23)	453 (20)	929 (21)	936 (23)	1,024 (69)	4,487
2012 - 2014	1,539 (67)	324 (12)	810 (19)	1,060 (20)	1,152 (22)	496 (20)	1,020 (24)	1,031 (26)	966 (27)	3,369

IN BRACKET THE NUMBER OF PROPERTIES

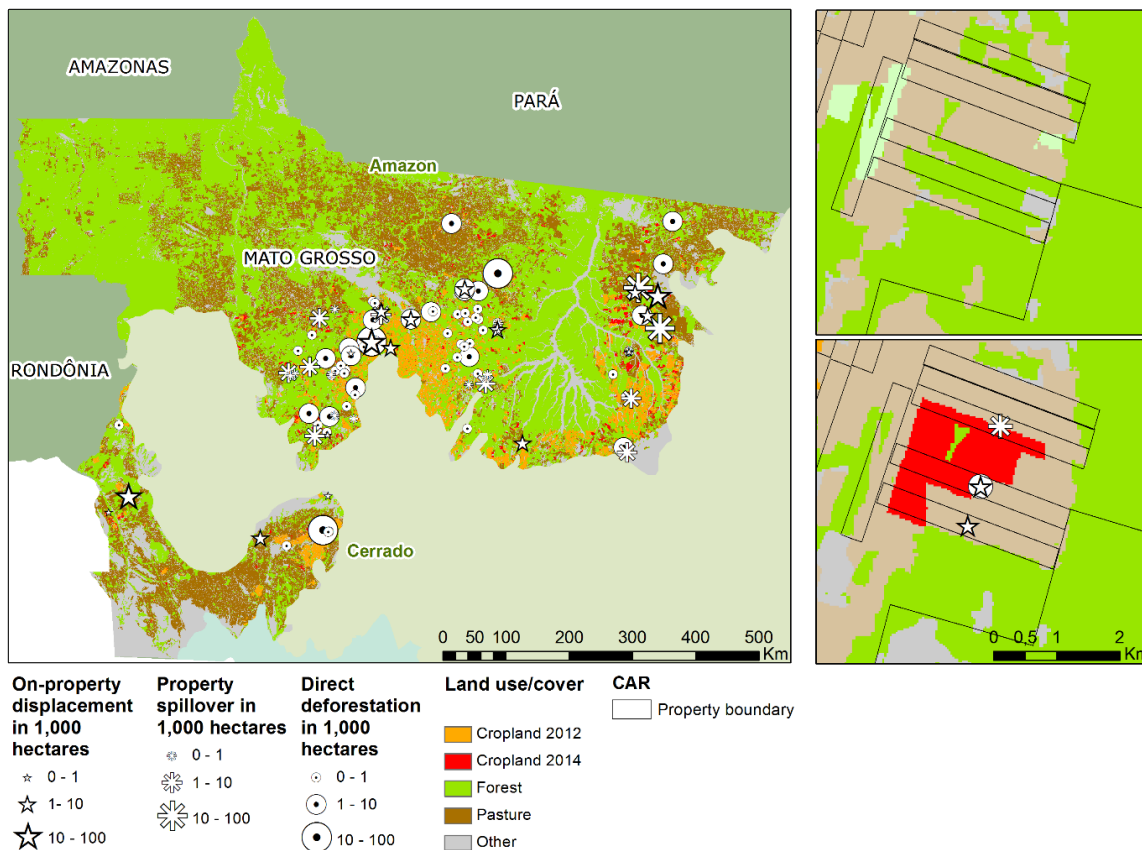


Figure III-4: Deforestation associated with soybean expansion between 2012 and 2014, identifying on-property displacement, property spillover, and direct deforestation (11.5)

#### 4 Discussion

This is the first analysis providing estimates of deforestation for soybean expansion, accounting for *direct* deforestation, associated *on-property displacement*, and *property spillover* deforestation for the Amazon biome of Mato Grosso. We used mapped croplands to approximate deforestation for soybean, following the observations, that 97% of croplands in the Amazon region of Mato Grosso were used for soybean cultivation (Arvor et al., 2011b), and increases in soybeans production were the dominant force, underlying the expansion of croplands (Fearnside, 2001; Arvor et al., 2011b; Macedo et al., 2012).

Our results indicated a reduction of deforestation, similarly for soybeans and pastures within the observed properties between 2004 and 2014. Direct deforestation rates for soybean decreased from 56.3 to 1.5 thousand hectares per year between 2004 and 2014. These findings corroborate earlier analysis, suggesting a reduction of deforestation for soy production (Rudorff et al., 2011; Macedo et al., 2012; Grupo de Trabalho da Soja (GTS), 2016; Imaflora, 2016). However, we mapped that in 2014, on-property displacement and

property spillover added 1.8 thousand hectares to soybean associated deforestation. (Table III-1; I1.5).

On-property *direct* deforestation for soy production and *on-property displacement* occur within the same property. Hence, both processes can unambiguously be connected with the farmer's decision to expand the cropping areas. Both deforestation processes occurred throughout our ten-year observation period. However, a distinct response to the implementation of the Soy Moratorium via *on-property displacement* deforestation, as hypothesized by Rausch and Gibbs (2016), could not be identified. In fact, *on-property displacement* deforestation declined following our first period of analysis.

The finding that *on-property displacement* deforestation occurred already before the implementation of the Soy Moratorium is in line with findings of Macedo et al. (2012) and Morten et. al. (2016) who observed most soybean expansion to occur over pastures, while farmers deforest for pastures. Nonetheless, after the implementation of the moratorium, the reduction of *on-property displacement* deforestation, especially on large and mega properties did not decrease by a similar magnitude as *direct* deforestation. Between 2004 and 2008 *on-property displacement* deforestation contributed an additional 5.4% to *direct* deforestation for soybean expansion. In 2012-2014, the share of *on-property displacement* deforestation increased to about 52.7% (Table III-1: I1.5). Moreover, compared to the previous period, on-property displacement deforestation 2012-2014 increased considerably accounting for moderate to strong intensification (Table III-1: I1.5, I2). This increase coincided with rising soybean prices in 2012 throughout 2014 (World Bank, 2017). If farmers identified *on-property displacement* as a strategy to respond to favorable market conditions, this would significantly undermine the effectiveness of the Moratorium to halt deforestation under favorable market conditions.

*Property spillover* deforestation related the expansion of soy cultivation over pastures, to deforestation for cattle ranching in its neighboring properties. We used this spillover process to account for the landowners owning or renting multiple properties. Decisions of these farmers are not limited to one property but affect their entire land holdings.

Overall, we estimated *property spillover* deforestation to considerably increase deforestation associated with cropland expansion. Similarly, to *direct* deforestation, we estimated a decline of *property spillover* deforestation following the first observation period (2004-2008). We observed a decline from 7.4 to 1.0 thousand hectares of deforestation per year (2004-2008, I1.5; 2012-2014, I1.5). An increasing share of medium properties during the last observation

period, contributing to property spillover deforestation might indicate a process of land concentration with one farmer renting or owning multiple medium sized properties.

Accounting not only for *direct deforestation*, deforestation related to soybean expansion more than doubled in 2012 to 2014 (Table III-1: I1.5). Accordingly, the reported numbers of deforestation for soybean production, adding up to 37.16 thousand hectares for Mato Grosso, Pará, and Rondônia, between 2008 and 2015 (Imaflora, 2016), are likely significantly higher if *on-property displacement* deforestation and *property spillover* deforestation were included. However, the reported estimates of the Soy Moratorium are under additional risk to underestimate deforestation for soybean production due to the coarse resolution of the monitoring system. Between 2008 and 2010, the MMU of the Soy Moratorium monitoring system only allowed detection of soybean cultivation larger than 100 hectares. Since 2010 the MMU was reduced to 25 hectares (Imaflora, 2016). However, this size threshold may be too coarse to reliably map direct deforestation for soybean expansion, considering that the size of deforestation patches has decreased during the last decade. Recent discussions have even questioned the effectiveness of the PRODES deforestation monitoring system regarding its MMU of 6.25 hectares considerably finer than the minimum size monitored by the Soy Moratorium (Rosa et al., 2012; Richards et al., 2016).

The contribution of actors to the reduction of deforestation was largest among the large and mega properties. Nevertheless, these properties continue to be the main contributors to *direct* deforestation for crop expansion (except 2010-2012), and *on-property displacement* deforestation throughout our observation period (Figure III-3; Table III-1). These results are in line with the conclusions of Richards et al. (2015) and Godar et al. (2014) and expand their findings towards *on-property displacement* deforestation for cropland expansion. Different to *direct* and *on-property displacement* deforestation, contributions of *property spillover* deforestation showed a high variability among property categories. While mega properties contributed most to *property spillover* deforestation within the first observation period, this changed in favor of large properties, and thereafter to medium properties between 2012 and 2014. This increase of smaller properties contributing to property spillover deforestation may suggest an increasing land concentration, with multiple properties being managed by fewer farmers.

Contributing to the discussion on actor balanced policies, we agree with Richards et al. (2015), to continue targeting large properties to protect the forest within those properties against illegal deforestation. However, we do not necessarily understand the discussion of



Richards et al. (2015) and Godar et al. (2014) as mutually exclusive. Better monitoring (increasing the MMU) and law enforcements, required to target large actors, similarly improve the mapping of deforestation on small properties. Additional incentive-based policies targeting small farmers may add crucial impulses to decrease deforestation among all actors.

Concerning the effectiveness of the Soy Moratorium, our analysis adds valuable knowledge on deforestation indirectly linked to the expansion of soybean due to its interaction with cattle ranching. *On-property displacement* deforestation could be targeted within the Soy Moratorium by either monitoring all on-property deforestation incidents or by combining and enforcing the compliance with the Soy Moratorium and environmental laws, such as the Brazilian Forest Code (Azevedo et al., 2015). Better implementation and monitoring of the Cattle Agreements may additionally reduce deforestation for cattle ranching, and thus indirectly reduce deforestation linked to soybean expansion. This said we stress the need for a better integration between the supply chain actors, the soybean and beef purchasing companies, and the governmental institutions responsible for the implementation and enforcement of the policies aiming to control deforestation. The CAR system institutionalized under the Brazilian Forest Code is a significant step towards implementation and enforcement of environmental laws and regulations (Código Florestal, 2012).

As noted, and accounted for by the different intensification factors in our analysis, large potentials for cattle ranching intensification affecting the identification and quantification of *on-property displacement* and *property spillover* deforestation exist. However, our estimates of indirect deforestation are simplistic in perspective of farmers' complex decision-making. On the one hand, soybean expansion is often accompanied by a reduction of cattle herd size. This would result in an underestimation of *on-property displacement* and *property-spillover* deforestation. On the other hand, intensification practices also include integrated crop-livestock systems (Gil et al., 2015), not covered by the classification schemes of TerraClass. Additional uncertainties derive from the dataset used for the analysis. These include uncertainties emerging due to the spatial intersect of the CAR and TerraClass land cover data, possible classification errors of TerraClass (INPE, 2015).

## 5 Conclusion

Expansion of croplands in the Amazon biome of Mato Grosso does not only lead to *direct* deforestation but also *on-property displacement* deforestation and possibly to *property spillover* deforestation. Croplands in the Amazon of Mato Grosso are almost entirely used for soybean production, rendering related deforestation relevant within the framework of the Soy Moratorium. We observed indirect deforestation related to the expansion of soybean to double in the period of 2012-2014 compared to earlier years. Indirect deforestation was defined as *on-property displacement* deforestation and *property spillover* deforestation. However, we did not identify increased indirect deforestation triggered by the implementation of the Soy Moratorium. *On-property displacement* and *property spillover* deforestation decrease after the implementation of the Moratorium. However, we observed increasing rates within our last observation period (2012-2014), coinciding with increasing prices for soybeans. The largest contributions to *direct* and *on-property displacement* deforestation originated from large and mega properties, which at the same time host the largest areas of remaining forests. This supported the discussion on policies to target large actors to reduce and control future deforestation. Based on the results of this analysis, we stress the need to account for the interactions between the different agricultural commodities. A better integration between the supply chain actors, the soybean and beef purchasing companies, and the governmental institutions responsible for the implementation and enforcement of the policies aiming to control deforestation will be crucial to future decreases of deforestation.

## Acknowledgments

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## Supplement Information

Table SI III-1. Size of forest within properties cultivating croplands.

Year	Area of forest in within properties cultivating croplands in hectares per property size category					Total forest in properties in hectares	Percent of total forest in properties
	micro	small	medium	Large	mega		
2004	4527.00	27777.33	138870.90	489617.10	778084.83	1438877.16	2.43
2008	12762.18	46338.48	221895.09	797606.10	1225814.22	2304416.07	18.73
2010	11181.42	49601.97	242223.66	848602.89	1258025.04	2409634.98	19.68
2012	11809.35	49631.94	251989.74	890582.94	1400616.00	2604629.97	21.40
2014	10854.45	47833.29	268692.75	1090472.67	1672619.58	3090472.74	25.58

Table SI III-2. Cropland area within properties

Year	Area of croplands within properties in hectares per property size category					Total cropland area within properties
	micro	small	medium	large	mega	
2004	22863.27	70478.37	218011.23	329505.75	224555.58	865414.20
2008	61499.97	120215.88	363521.34	628369.11	444936.24	1618542.54
2010	63363.96	131723.01	408293.82	704986.65	528702.57	1837070.01
2012	78080.76	145479.78	434279.70	796454.01	587020.68	2041314.93
2014	71404.11	138411.81	432029.88	897106.86	670000.77	2208953.43

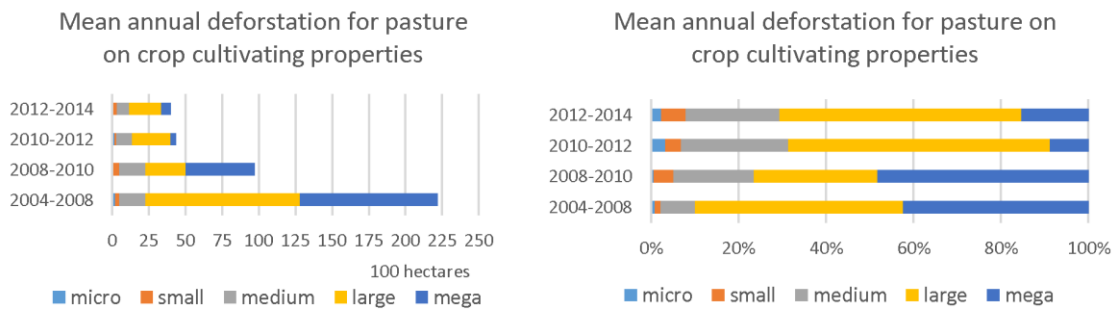


Figure SI III-1. Deforestation for pasture on crop cultivating properties



Chapter IV:  
**Scenarios of land use change in a deforestation  
corridor in the Brazilian Amazon: combining two  
scales of analysis**

*Regional Environmental Change, 2017*

Florian Gollnow, Jan Göpel, Leticia de Barros Viana Hissa, Rüdiger  
Schaldach, Tobia Lakes

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## **Abstract**

Local, regional, and global processes affect deforestation and land use changes in the Brazilian Amazon. Characteristics are: direct conversions from forest to pasture; regional processes of indirect land use change, described by the conversion of pastures to cropland, which increases the demand for pastures elsewhere; and teleconnections, fueled by the global demands for soybeans as animal fodder. We modeled land use changes for two scenarios *Trend* and *Sustainable Development* for a hot spot of land use change along the BR-163 highway in Mato Grosso and Pará, Brazil. We investigated the differences between a coupled modeling approach, which incorporates indirect land use change processes, and a noncoupled land use model. We coupled the regional-scale LandSHIFT model, defined for Mato Grosso and Pará, with a subregional model, alucR, covering a selected corridor along the BR-163. The results indicated distinct land use scenario outcomes from the coupled modeling approach and the sub-regional model quantification. We found the highest deforestation estimates returned from the subregional quantification of the *Trend* scenario. This originated from the strong local dynamics of past deforestation and land use changes. Land use changes exceeded the demands estimated at regional scale. We observed the lowest deforestation estimates at the subregional quantification of the *Sustainable Development* story line. We highlight that model coupling increased the representation of scenario outcomes at fine resolution while providing consistency across scales. However, distinct local dynamics were explicitly captured at subregional scale. The scenario result pinpoint the importance of policies to aim at the cattle ranching sector, to increase land tenure registration and enforcement of environmental laws.

## 1 Introduction

Land use models describe the interplay between different driving factors within land systems (Verburg et al., 1999; Schaldach et al., 2011). They are often used to explore dynamics and envision plausible paths along which future land use distribution could unfold, presented in the form of land use scenarios. Most often, assessments aim to inform policy makers, identify hot spots of change, or raise awareness of undesired long-term developments within land systems. Environmental concerns about deforestation in the tropical regions around the world led to a large number of land use change scenario analyses, especially within the Amazon biome (Lapola et al., 2010b; Dalla-Nora et al., 2014).

Researchers have developed and applied land use models for different scales, purposes, and regions. Methods vary between cellular automata or rule-based approaches, empirical or statistical models, agent-based models, macroeconomic models, land use accounting models, and integrated approaches that combine different methodologies (Alcamo et al., 2006; Brown et al., 2014). The increasing understanding of the complexity of land use change and linkages within the earth system (e.g., land use changes that depend on teleconnections, indirect land use changes, or displacement) calls for reconsidering the traditional understanding of a closed system at one spatial scale (Lapola et al., 2010a; Arima et al., 2011; Meyfroidt et al., 2013; Dalla-Nora et al., 2014; 2014; Richards et al., 2014). However, such processes and feedbacks of indirect land use changes from global to regional to local scales are rarely addressed in land use modeling studies (Rosa et al., 2014).

Some of the most prominent scenario assessments refer to deforestation in the tropics, where global, regional, and local perspectives on climate regulation, biodiversity conservation, individual livelihood, and national interests, among others, meet. For the Brazilian Amazon, a number of scenarios have been published (Laurance et al., 2001; Soares-Filho et al., 2001; Soares-Filho et al., 2004; Soares-Filho et al., 2006; Wassenaar et al., 2007; Moreira, 2009; Lapola et al., 2010b; Lapola et al., 2010a; Assis et al., 2011; Maeda et al., 2011; Oliveira et al., 2013; Rosa et al., 2013; Rosa et al., 2014; Verburg et al., 2014; Aguiar et al., 2016). Dalla-Nora et al. (2014) critically assessed key elements of the different scenarios and realized that most scenario models failed to capture the amount of deforestation over recent decades. Additional shortcomings relate to a lack of transparency in terms of quantifying, calibrating, and validating the models (Rosa et al., 2014). Recommendations for future scenario assessments include integrating global and regional models to improve the structure and consistency of Amazonian land use/cover change assessments (Alcamo et al., 2006;

Dalla-Nora et al., 2014). Cross-scale linkages of land use change processes may be especially true for regions that are dominated by the production of agricultural goods for export markets. Soybean demand as animal fodder for European and Chinese markets has fueled the soybean industry in Brazil, where it has been linked to extensive conversions of natural vegetation (Brown-Lima et al., 2010; Arima et al., 2011; Gollnow and Lakes, 2014; Godar et al., 2016; FAO, 2017). Consequently, the increase in demand for animal fodder can be understood as an important driver of soybean expansion and deforestation in the Brazilian Amazon (Macedo et al., 2012; DeFries et al., 2013).

Multiscale modeling approaches to model deforestation and land use change have been suggested by different authors. For example, Moreira et al. (2008) coupled a regional ( $25 \times 25 \text{ km}^2$ ) with an agent-based ( $1 \times 1 \text{ km}^2$ ) land use model to assess future deforestation in São Félix do Xingu, embedded within the context of the Brazilian Amazon. The coupling covered the amounts of prospected deforestation and also included a bottom-up linkage in case the expected amount at the regional scale could not be allocated within the subregional model. This could occur, for example, if the network of protected areas were expanded or other restrictions on deforestation were implemented. Verburg et al. (1999) provided a spatially explicit modeling approach for Ecuador, coupling two spatial scales of analysis that both covered the entire country. The authors modeled the spatial linkages of the land use changes between  $9 \times 9 \text{ km}^2$  and  $35 \times 35 \text{ km}^2$  grids, including top-down and bottom-up linkages. However, the spatial coarseness of both scales in the modeling experiment avoided common challenges of data comparability and accuracy at different spatial scales.

Data on the spatial configuration of land use and cover is a crucial input for most land use models. It determines the initial land use patterns within the study region. Most often, information on land use and cover derives from remote sensing data classification. Whereas high-resolution land use data is often available only for selected regions of a defined extent, moderate- to coarse-resolution data are available on a global scale but may not be reliable for regional analysis (Herold et al., 2008; Kaptué Tchuenté et al., 2011). Combining different land use data sets at different scales involves challenges related to spatial accuracy, precision, and the thematic comparability of the classifications. It remains challenging to develop and apply approaches that link different scales of land use models, including different sources of spatial information on land use, to provide consistent scenarios across scales (Alcamo et al., 2006; Dalla-Nora et al., 2014).



The selected region for this study is situated within the federal states of Mato Grosso (MT) and Pará (PA) in Brazil along the BR-163 highway, which traverses the Amazon rainforest. MT became Brazil's largest soybean-producing state for export markets in recent decades (Brown-Lima et al., 2010; Macedo et al., 2012; DeFries et al., 2013). Soybean expansion came mostly at the expense of direct conversion of savanna in MT but also indirectly led to deforestation through pasture displacement and cattle ranching in MT and PA (Arima et al., 2011; Boucher et al., 2013; Gollnow and Lakes, 2014; Richards et al., 2014; Gibbs et al., 2015; Arima et al., 2016). Particularly during the soybean boom in the early 2000s, land speculation, the strong appreciation in land value, and the expansion of cropland on pasture was linked to the displacement of cattle production, which led to increased deforestation in the Amazon biome (Gollnow and Lakes, 2014; Richards et al., 2014).

Within this setting, we explore multiscale land use modeling for two scenarios. We coupled a regional scenario quantification and spatial allocation with a subregional allocation model and compared these with a subregional quantification. At the regional scale, we used the LandSHIFT modeling framework (Schaldach et al., 2011), and at the subregional scale, we used the alucR framework (Gollnow, 2015). We used different land use and cover maps with the two scales based on the availability of a reliable and detailed map (i.e., TerraClass) for the subregion (INPE, 2015; Almeida et al., 2016). This map was not available for the spatial extent of the regional scale model. Instead, we used the global land cover product provided by MODIS (Friedl et al., 2010). Combining two data sets at the different scales required new approaches of model coupling between scales. Story lines of future regional development have been developed and quantified within the interdisciplinary project CarBioCial and discussed with selected stakeholders in Brazil ([www.carbiocial.de](http://www.carbiocial.de)).

We derived the following research questions:

1. What are the differences in the 2010 land use and cover maps between the subregional and the regional land use classifications that will affect the results of the coupled land use scenarios?
2. What are advantages of cross-scale modeling vs. subregional model quantification of land use change scenarios?
3. What are possible scenarios of land use change along the BR-163 highway following coupled and subregional model quantification?
4. How does the amount of deforestation vary between the different scenarios?

## 2 Methods

### 2.1 Study area

The study area is situated within the Brazilian Amazon, along the BR-163 highway in the states of MT and PA (Figure IV-1). These two states account for approximately 67% of the Brazilian Legal Amazon deforestation through 2015 and continue to present the highest forest loss rates among the Brazilian Legal Amazon states (INPE, 2017). The region along the BR-163 has been one of the most dynamic forest frontiers in the two states (Fearnside, 2007). At the regional level, we calculated land use scenarios for both states. At the subregional level, we selected a buffer of 100-km width along the BR-163 starting from Sinop in the south and reaching north to Morais de Almeida, south of Parque Nacional do Jamaxim (Figure IV-1). This corridor follows the dominant occupation history along the highway from south to north (Fearnside, 2007; Coy and Klingler, 2011; Müller et al., 2016). In MT, land use is dominated by large-scale soybean, maize, and cotton production, mostly cultivated in double-cropping systems (Arvor et al., 2011b; Lapola et al., 2014). Moving north toward the border of PA, a transition to large-scale cattle ranching occurs, with integrated crop and cattle management emerging (Gil et al., 2015). In the south of PA, cattle ranching is the dominant land use. Here, weak governance and uncertain land tenure rights prevail (Fearnside, 2007; Richards, 2012b; Gil et al., 2015).

Following the increase in deforestation rates in the early 2000s, a set of measures, policies, and institutional agreements were put into action to control and prevent deforestation within the region. Most important were the 2004 PPCDAm (Action Plan to Prevent and Control Deforestation in the Amazon); the Soy Moratorium, implemented in 2006; and the Beef Moratorium that was agreed on in 2009 (Boucher et al., 2013). The PPCDAm combines a series of strategies: expanding the protected areas network, increasing and improving monitoring, enforcing environmental laws, and supporting the Rural Environmental Registry (CAR) and sustainable production systems (MMA, 2013). The Soy Moratorium and Beef Moratorium are pledges that were agreed to by the major soybean companies and beef traders, respectively, to ensure that their products would not be produced on newly deforested lands (Boucher et al., 2013). These actions, in combination with changes in global prices for agricultural goods, led to a 68.2% decrease in deforestation rates in 2015 compared with the past decade's (1996–2006) baseline (Rudorff et al., 2011; Assunção et al., 2012; Boucher et al., 2013; Assunção et al., 2013b; Gibbs et al., 2015; INPE, 2017). However, in

2013, 2015, and 2016, deforestation increased, although at significantly lower rates compared with the beginning of the remote sensing monitoring program (INPE, 2017).

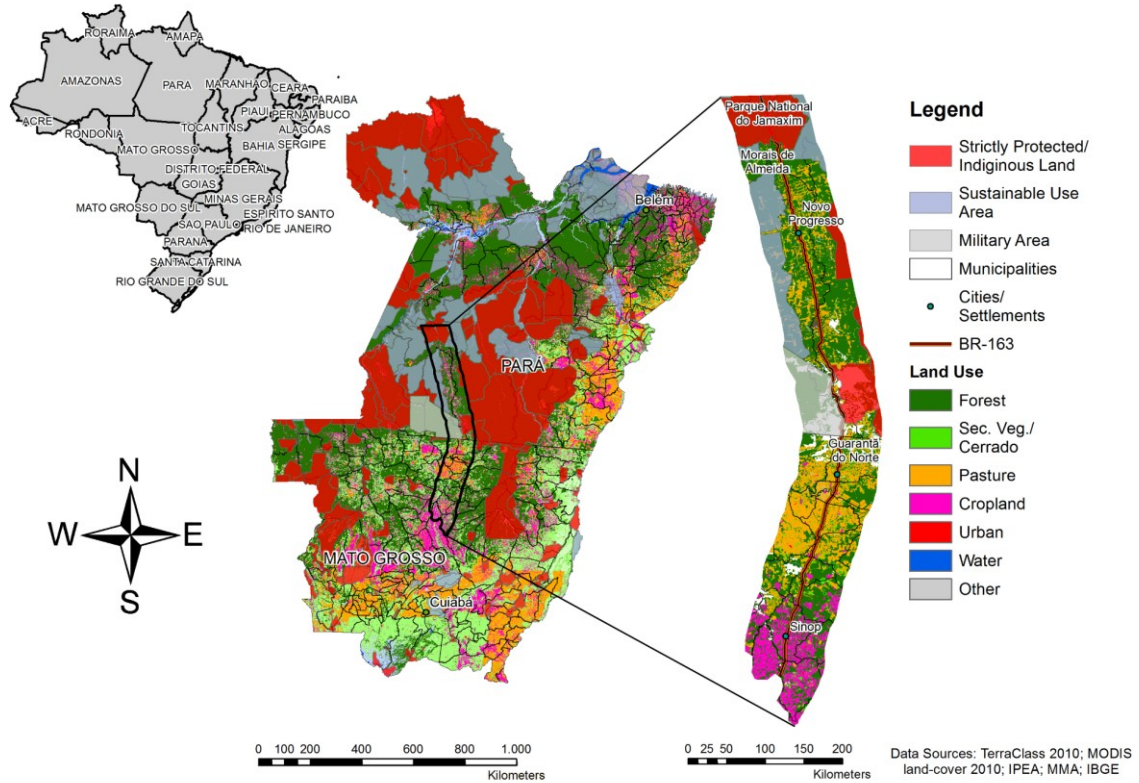


Figure IV-1: Study region

## 2.2 Land use models and multiscale modeling

We calculated spatially explicit scenarios of subregional land use change for the BR-163 corridor following two approaches. The first was to combine two scales of analysis, which we referred to as coupled modeling. Here, we calculated land use scenarios for MT and PA and used the results as input to quantify the amount of land use change within the subregion along the highway. The second modeling approach quantified the scenario assumptions derived from the story line based on spatially explicit data for the municipalities in the BR-163 subregion.

For the coupled modeling approach, we combined the scenario results from LandSHIFT with the alucR modeling framework. We describe each model in more detail below. When it was beneficial for the respective scale, we used different data sets for the different scales within the modeling frames (Table IV-1). Most important, we used a different land use and cover maps for the initial land cover distribution. At the subregional scale, we applied the

TerraClass land use classification (INPE, 2015). For the regional MT and PA scenarios, we used the MODIS product (Friedl et al., 2010). The fine spatial resolution ( $90 \times 90 \text{ m}^2$ ) of the subregional model allowed us to include the protection of riparian areas as determined by the Brazilian environmental law (Código Florestal).

Both land use modeling frameworks include a nonspatial macrolevel and a spatially explicit microlevel. The scenario quantification specifies the macrolevel. Here, quantitative future demands for agricultural production or land requirements and population change according to global and regional socioeconomic and agricultural developments are defined. At the microlevel, these land use scenario demands are allocated spatially, and additional spatial restrictions (e.g., locations where no land use conversion is allowed) are defined.

### ***2.2.1 LandSHIFT***

The LandSHIFT modeling framework was designed for regional- to global-scale land use scenario analysis and has been tested for different case studies in Brazil (Lapola et al., 2010b; Lapola et al., 2010a; Alcamo et al., 2011; Schaldach et al., 2011). It is organized into land allocation submodules that correspond to the different land use subsystems: settlement, cropland, and pasture based on Turner et al. (2007). A multi-criteria analysis determines the suitability of a certain location for cropland, pastures, and settlements, including those factors provided in Table IV-1. The allocation follows a defined hierarchy: first, settlement areas are distributed; second, cropland; and third, pastureland, each at its most suitable location. Amounts of cropland change depend on the potential crop yields provided by the LPJmL model (Bondeau et al., 2007) in combination with the scenario assumptions. Changes in pasture area depend on the net primary productivity of the locations, also provided from the LPJmL model, and the scenario assumption relating to the development of the livestock sector. The scenarios may also include a certain rate of agricultural intensification (Schaldach et al., 2011). The initial land use map combines a reference map and a quasi-optimal distribution of the land use types derived from official statistics on agricultural production and population. Here, we combined the MODIS land cover product resampled to  $900 \times 900 \text{ m}^2$  with official census data acquired from the Brazilian Institute of Geography and Statistics (IBGE) to generate a representation of land uses in MT and PA.

### **2.2.2 *alucR***

The *alucR* model framework follows a statistical evaluation of land use suitabilities. Similar to LandSHIFT, the land use types are urban areas, cropland, and pastureland. We used best subset logistic regression analysis to estimate the locational suitability for each land use class (McLeod and Xu, 2015). We selected the spatial factors for estimating suitability based on earlier studies, and have summarized them in Table IV-1 (Aguiar et al., 2007; Espindola et al., 2012). Our model selection was guided by the Akaike information criteria (AIC). The AIC evaluates the trade-off between model complexity and model fit (McLeod and Xu, 2015). Amounts of land use defined at the macrolevel are allocated according to the relative suitability for each land use class (Gollnow, 2015). This allocation procedure is generally described as simulating the competition between land uses (Verburg et al., 2006).

We calibrated the competition between land use classes according to the transition and persistence of land uses, defined within the trajectory and elasticity matrix (Table SI IV-1 and Table SI IV-2). The elasticity settings build the core part of the calibration process. They adjust the suitability values for a certain land use based on the current land use categories. For example, a pixel classified as urban is very likely to stay urban in the next year rather than being relocated. This is why the suitability for urban use at this location should be increased to guarantee class persistence. We calibrated the model according to the elasticities using TerraClass 2014, the most recent year of comparable land use information. We iteratively adjusted the elasticities based on the overall accuracy of the land use change maps considering all observations. We calculated the accuracy by comparing the “true” changes between the TerraClass 2010 and 2014 classifications with the modeled changes for 2014, allocating the observed amounts of change derived from the TerraClass maps.

Spatial restrictions play an important role in both land use modeling approaches. Depending on the scenarios, spatial restriction of land use change refers to strictly protected areas, indigenous land, sustainable use areas, military areas, and protected riparian areas.

## **2.3 Scenario building**

We selected two scenarios that were developed as part of CarBioCial. They describe qualitative (story lines) and quantitative developments with a focus on the BR-163 highway. The story lines encompass possible ecological, societal, economic, and political developments in the study region until 2030 and were translated into their potential meaning for population change, agricultural development, and land use policy, following a similar

structure to the story and simulation approach described by Alcamo (2008). We extracted statements from the story lines that referred to each of the three groups and interpreted them in terms of their potential meaning for the land use modeling process (Table IV-2). We then translated these qualitative interpretations into either numerical values of agricultural production and population change or spatially explicit land use change constraints, referring to protected areas or the Soy Moratorium (no cropland expansion in areas deforested after 2006) and Beef Moratorium (no pasture expansion in areas deforested after 2010). We extrapolated past trends derived from regional statistics and adjusted them following the scenario assumptions.

In brief, the *Trend* story line describes the continuation of current land use practices characterized by increasing demands for agricultural goods, the paving of the BR-163 highway, and ongoing intensification of agrarian production. Increasing trends in crop and cattle production and population changes are the dominant drivers for calculating future land requirements. In this story line, protected areas play an important role for preserving the primary rainforest. However, inadequate monitoring and law enforcement was expected to lead to a de facto reduction of protected area size. We derived the numerical values for agricultural production and population changes for the scenario period of 2010 to 2030 by least-squares linear extrapolation of historical trends from 1973 to 2000 (Table SI IV-3).

The second scenario story line was developed under the premises of *Sustainable Development*. The main foci with respect to the quantification process were a global and national change to a vegetarian-oriented diet, a regional reduction in population growth, and an increase in crop productivity. Expected sociopolitical changes included a social model of participation, citizenship, and law enforcement, food sovereignty, local sustainable development initiatives, a growing demand for certified agrarian goods, and clarification of land rights.

### ***2.3.1 The model coupling approach***

For our coupled modeling approach, we translated from story line to numerical values based on the regional statistics for MT and PA between 1973 and 2000. The derived quantifications summarized in Table IV-2 served as input for LandSHIFT, which generated spatially explicit land use change scenarios for MT and PA at five-year intervals. We extracted the amount of land use change for the BR-163 corridor subregion from the LandSHIFT regional scenarios and input them into alucR (Figure IV-2). We applied simple linear interpolation for each year

between the five-year model steps generated by LandSHIFT to disaggregate the quantities to the annual land use changes required for alucR.

### 2.3.2 Subregional approach

The subregional land use modeling approach followed the more traditional quantification process based on the historic development of the subregion (Figure IV-2). We used past developments derived from the intersecting municipalities (1973-2000) along the BR-163 corridor to translate the story lines into numerical values for agricultural production and population change (Table SI IV-4). We spatially allocated the derived quantities of land use change with the same alucR model as that for the subregion in our coupled modeling.

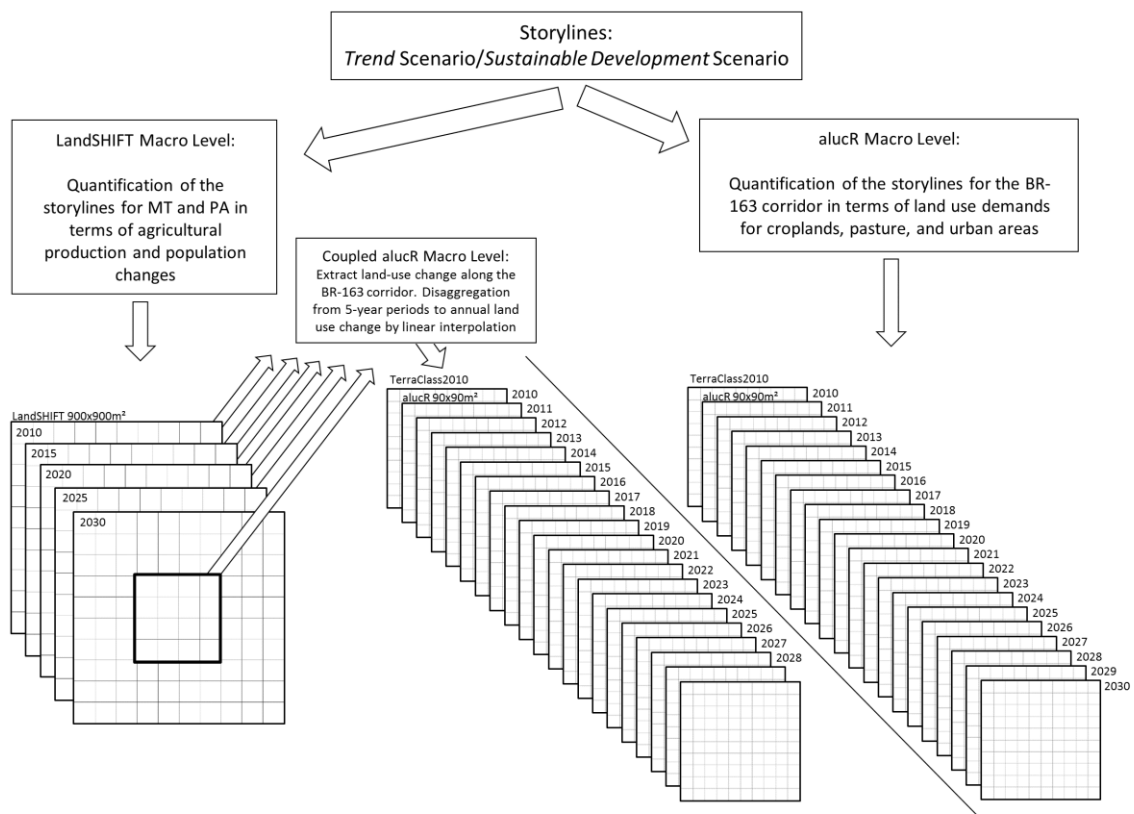


Figure IV-2: Schematic figure of the coupled modelling (*left*) and the subregional quantification (*right*)

## 2.4 Data

Detailed information on land use and cover as input for the land use models is crucial for computing scenarios of future land use distribution. At the subregional scale, the Brazilian Institute for Space Research (INPE) provided a detailed map of post deforestation land use, TerraClass, available for the years 2004, 2008, 2010, 2012, and 2014, with a minimum mapping unit of 6.25 ha ( $250 \times 250 \text{ m}^2$ ). These maps are based on visual interpretation of Landsat satellite data in combination with MODIS phenology data and the PRODES deforestation mask (Almeida et al., 2009; INPE, 2015; Almeida et al., 2016; INPE, 2017).

Such detailed information was not available at the regional scale throughout all of MT and PA. Instead, we employed the 2010 MODIS product ( $500 \times 500 \text{ m}^2$ ) (Friedl et al., 2010), aggregated to  $900 \times 900 \text{ m}^2$ , to initiate the regional-scale land use modeling. In LandSHIFT, we spatially allocated land use as derived from agricultural statistics on crop types, livestock units, and population counts at the locations of the relevant land cover classes, following a quasi-optimal allocation algorithm (Schaldach et al., 2011). We hereafter refer to the resulting land use map as LandSHIFT 2010.

We harmonized the land use classes between the two maps to match similar categories between TerraClass 2010 and LandSHIFT 2010. The categories were croplands, pastures, urban areas, forests, secondary vegetation, water, and other land use and cover types (Table SI IV-5). We based the suitability analyses for cropland, pastureland, and urban areas on the data summarized in Table IV-1.

We included different categories of protected areas in the scenarios (Table SI IV-2). If protection was enforced, the model prevented any expansion of land use within those areas. Additionally, the *Sustainable Development* scenario stressed the demand for certified agrarian goods. As such, we prohibited cropland expansion in areas deforested after 2006 (Soy Moratorium) and pasture expansion in areas deforested after 2010 (Beef Moratorium).



Scenarios of land use change in a deforestation corridor in the Brazilian Amazon:  
combining two scales of analysis

Table IV-1: Data sets for model specification

<b>Data category</b>	<b>Description</b>	<b>Model</b>	<b>Source</b>
<b>Land use/cover</b>	Land use/cover (TerraClass 2010, 2014)	alucR	INPE, 2015
	Land use/cover (MODIS 2010)	LandSHIFT	MCD12Q1, GLCF, 2014
<b>Suitability factors</b>	Slope	LandSHIFT / alucR	SRTM (United States Geological Survey (USGS), 2000)
	River density Distance to rivers	LandSHIFT alucR	Density (LandSHIFT): Lehner and Grill, 2013 Distance (alucR): Agência Nacional de Águas - ANA, 2010
	Distance to roads (all, paved, unpaved)	LandSHIFT / alucR	IBGE, 2010b
	Precipitation 2000-2008 (mean, min, max)	alucR	NASA, 2015
	Distance to cities	alucR	TerraClass 2010 Urban (INPE, 2015)
	Aptitude for mechanized crop production (1: very aptitude; 2: aptitude; 3: not aptitude)	alucR	Soares-Filho et al., 2014
	Elevation	LandSHIFT	SRTM30 (United States Geological Survey (USGS), 2000)
	Distance to major markets	LandSHIFT	ESRI - Environmental Systems Research Institute, Inc, 2000
	Crop yields, grassland NPP	LandSHIFT	LPJmL model (Bondeau et al., 2007)
	Global livestock density	LandSHIFT	Wint and Robinson, 2007
<b>Spatial rules</b>	Protected areas: Strictly Protected areas (SP); Indigenous Lands (IL); Sustainable Use areas (SU); Military Areas (MA)	LandSHIFT / alucR	SP, IL, SU: MMA, 2015 MA: Zoneamento Ecológico-Econômico da Rodovia BR-163 (ZEE), 2008
	Riparian Protected Areas (RPA): estimated based on river dataset (max. 90m, min 60m buffer)	alucR	Agência Nacional de Águas - ANA, 2010
	Areas deforested before 2006 (derived from PRODES)	alucR	INPE, 2017
<b>Main datasets for the scenario quantification at macro level</b>	Crop production (in tons/y and ha/y) for 1974 to 2010) (see Table SI IV-3)	LandSHIFT alucR	IBGE, 2016
	Livestock units 1974 to 2007 (FAO, 2002) (see Table SI IV-3)	LandSHIFT alucR	IBGE, 2013
	Population estimates	LandSHIFT alucR	IBGE, 2010a

Table IV-2: Main aspects of the story line quantification (see Table SI IV-6 for story lines)

	Storyline assumption (Portuguese)	Scenario interpretation	Quantification
<b>Trend scenario</b>			
<b>Population change</b>	<p><i>"[...]a expansão de monoculturas e a concentração da terra no setor agrário, tendo como consequência a deslocação forçada contínua de trabalhadores rurais, agricultores familiares e pecuaristas de menor eficiência econômica. Uma parte dos deslocados encontrará trabalho nas novas aglomerações urbanas ao longo da BR-163, enquanto outros seguirão ao Norte da região, adiantando a conversão de floresta em pasto e lavoura na Amazônia. Em geral, se observa um crescimento de centros urbanos regionais. Por consequência, se ampliará o setor terciário. Essas cidades jovens apresentam configurações rural-urbanas específicas: muitas vezes os produtores agrários possuem residência na área urbana, dissolvendo assim a divisão clássica entre o meio urbano e o meio rural."</i></p>	<p>The storyline describes the continuation of current trend of population growth and migration developments.</p>	<p>Least squares extrapolation of urban population changes observed between 1974 and 2010. alucR: Estimated change rates were converted to area changes in relation to observed urban areas in TerraClass in 2010. LandSHIFT: Urban area changed according to the estimated population changes.</p>
<b>Agricultural development</b>	<p><i>"A estrutura da produção agrícola varia ao longo da rodovia de 1.780 km: no Mato Grosso, a dependência de multinacionais agrárias, a qual restringe as margens para decisões de inovação por causas econômicas, cresce proporcionalmente com a capitalização e as monoculturas (soja, milho, algodão)."</i></p>	<p>Monocultures of soybeans, corn and cotton continue to dominate the land use. Multinational companies mostly interested in economic growth dominate the production process.</p>	<p>Least squares extrapolation of past changes of crop production corrected for yield increases between 1974 and 2010 including the crop types listed in Table SI IV-3 alucR: Estimated change rates were converted to area changes according to cropland area in TerraClass in 2010. LandSHIFT: Tons of production were allocated according to land productivity derived from the LPJmL model.</p>
<b>Land use policy</b>	<p><i>"Existem numerosas áreas de proteção no Pará e no Mato Grosso, mas com uma administração deficiente, e raramente com monitoramento participativo. Ainda assim, possuem um papel importante na preservação de recursos naturais e da terra.[...] Os zoneamentos no nível macro, a falta de implementação da lei e a falta de recursos nos órgãos de fiscalização, juntos à pressão crescente sobre a terra, resultam no fato de que as reivindicações de justiça social contribuem para a diminuição das áreas de proteção"</i></p>	<p>Land use conversions within protected areas are limited but due to poor monitoring some illegal conversions occur. These results in a de facto reduction of protected areas size.</p>	<p>alucR: Land use conversions in sustainable use areas were allowed every 2<sup>nd</sup> year and in strictly protected and indigenous areas conversion every 4<sup>th</sup> year. No conversion in military areas. LandSHIFT: No land use conversions in protected, indigenous and military areas allowed.</p>
<b>Sustainable development scenario</b>			
<b>Population change</b>	<p><i>"A migração para a região pode crescer devido ao clima social favorável. Como não haverá migração por causa de deslocamento forçado, resultado de fatores socio-econômicos, a necessidade da migração inter-regional deixa de existir. No lugar deste tipo de migração, observa-se a migração inter-regional de profissionais e uma migração intra-regional equilibrada, ocasionado pela atração crescente das cidades médias. complementa-se o cenário pelo crescimento endógeno do espaço urbano e assim a estabilização da classe média urbana, que continua defendendo a sustentabilidade e justiça rural e urbana."</i></p>	<p>Inter-regional and intra-regional migration decreases, leading to a decrease of the projected population growth from the trend scenario.</p>	<p>Trend projections of population increase adjusted by a decrease of 7.5% every five years.</p>

Agricultural development	<p><i>“O papel de uma demanda que exige sustentabilidade ficou mais importante, assim, as maratórias de soja e de carne bovina, com respeito às exigências para a produção sustentável, são bem consolidadas, e os clientes as respeitam, seguindo a tendência global para um consumo de produtos sustentáveis. Na política local, ademanda externa e os efeitos dela são bem administrados. As distorções de preços no mercado mundial por subvenções (algodão, milho, leite...) se reduziram gradualmente; os produtos não certificados quase não encontram demanda, e as quotas de mercado para produtos ecologicamente produzidos aumentam, por exemplo para soja, carne e óleo de dendê. Incentivados pela estrutura da demanda, que visa a sustentabilidade, os mercados se adaptaram amplamente às formas agroecológicas de produção.”</i></p>	<p>The demand on certified ecologically produced plant based products increases. This is supported by a global trend towards certification and less meat-oriented diets.</p>	<p>Trend projections of plant-based products adjusted by an increase for beans, fruits, vegetables and soybeans (corrected for export losses due to decreasing demands for animal fodder).</p>
	<p><i>“De acordo com as apresentações acima, a população de gado é menor que nos outros cenários, por restrições impostas, assim como queda na demanda devido às mudanças nos hábitos alimentares.”</i></p>	<p>Livestock numbers decrease significantly, mostly due to changes in diets and certification needs.</p>	<p>Livestock reduction and accordingly pasture reduction by 70% compared to the projected trend scenario until 2030.</p>
Land use policy	<p><i>“No contexto do zoneamento todas as categorias de proteção foram revisadas, resultando em um consenso em relação à preservação de áreas de proteção existentes e à não exploração de áreas florestais. Isso resulta numa legislação de não exploração, incluindo o fomento às alternativas econômicas e pagamentos compensatórios”</i></p>	<p>The sustainability scenario focuses on the certification of production implemented with the Soy and Beef Moratorium. Similarly, protected areas are well monitored and hence will not exhibit changes in land use.</p>	<p>No conversion of land within protected areas (strictly protected areas, indigenous areas, and sustainable use areas). No conversion of areas deforested after 2006 to cropland or deforested after 2009 to pasture.</p>

### 3 Results

The results are organized as follows. First, we provide a quantitative comparison between the two initial land use data sets for the BR-163 corridor. Second, we describe the differences in the dynamics between the two states and the BR-163 subregion. Third, we compare and present the coupled and noncoupled scenario quantifications for the corridor. Finally, we describe the spatially explicit scenario results along the corridor and quantify the amount of deforestation until 2030.

#### 3.1 Comparison of LandSHIFT 2010 and TerraClass 2010 harmonized land use classifications for the BR-163 corridor

The amounts and spatial distributions of the initial land uses were critical for the process of coupling models across scales and for assessing future land use change scenarios. Here, we present the differences between the two land use maps, LandSHIFT 2010 and TerraClass 2010, for the BR-163 corridor. We found differences in both area and spatial distribution of land use and cover (Figure IV-4 and Figure IV-6). In total area, TerraClass 2010 reported approximately twice the amount of pasture within the corridor than LandSHIFT 2010 (TerraClass 2010: 17,862 km<sup>2</sup>; LandSHIFT 2010: 9,638 km<sup>2</sup>). Areas defined as cropland within TerraClass 2010 made up less than half the area defined in LandSHIFT 2010 (TerraClass 2010: 6,863 km<sup>2</sup>; LandSHIFT 2010: 17,862 km<sup>2</sup>). Urban areas were scarce in LandSHIFT (TerraClass 2010: 15 km<sup>2</sup>; LandSHIFT 2010: 3 km<sup>2</sup>). Natural vegetation cover,

which combined forest and secondary vegetation (Table SI IV-5), covered a larger area in TerraClass (TerraClass 2010: 50,246 km<sup>2</sup>; LandSHIFT 2010: 47,758 km<sup>2</sup>). A spatial comparison between the two maps indicated large differences in the northern part of the corridor. TerraClass 2010 identified mainly pasture areas in PA, whereas LandSHIFT 2010 classified large areas in southern PA as cropland (Figure IV-6). Within the central part of the corridor (north of MT), pasture use was dominant in TerraClass 2010, but a mosaic of croplands and pastures was present in LandSHIFT 2010. In the south of the study area (north-central MT) we found similar land use patterns, dominated by croplands within both classifications.

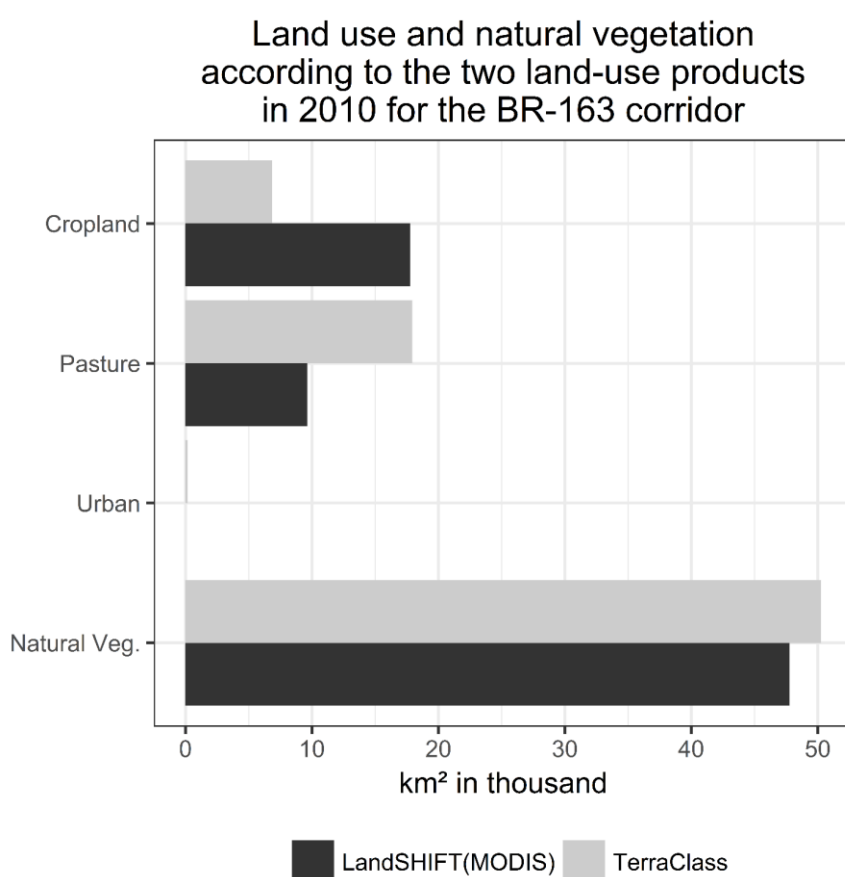


Figure IV-3: Land use and natural vegetation (forest and secondary vegetation) along the BR-163 in 2010 according to the initial land use and cover maps (LandSHIFT 2010 and TerraClass2010)

### **3.2 Comparison of the land use change dynamics at the regional scale vs. the subregional BR-163 corridor, derived from the coupled scenario quantification**

The *Trend* scenario: Pasture expansion was the dominant land-conversion process (Figure IV-4a). Especially in the second half of the scenario period, the BR-163 corridor was a hot spot of pasture expansion. In contrast with the slight decrease in cropland along the BR-163 corridor, the MT and PA areas experienced a slight overall expansion of cropland until 2030.

The *Sustainable Development* scenario: The coupled *Sustainable Development* scenario estimated a strong increase in land allocated for crop production and a decrease in pasture area (Figure IV-4b). This dynamic was less strong along the BR-163 corridor compared with the state (MT and PA) level. On one hand, this suggests that the BR-163 is less prone to large-scale crop expansion than are other regions in MT and PA, but on the other hand, a greater decrease in pastureland for all of MT and PA suggests the BR-163 region as more suitable for pasture.

Urban area demand increased slightly under the *Trend* and decreased slightly under the *Sustainable Development* scenarios in MT and PA. However, urban areas along the BR-163 corridor were left unchanged.

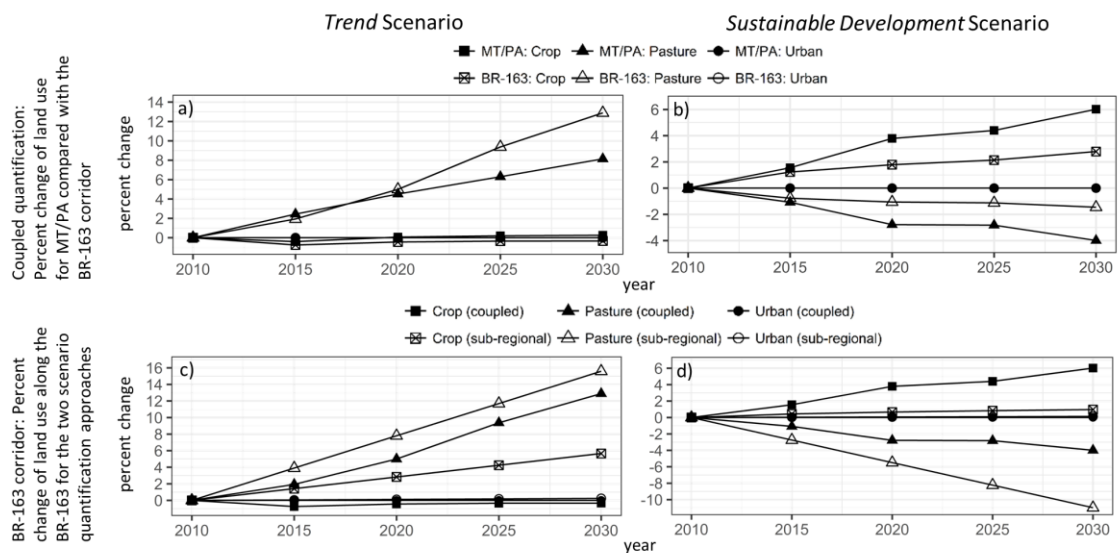


Figure IV-4: Comparison of land use changes in a, b MT and PA versus the subregion derived from the coupled quantification and c, d the land use change derived from the coupled and subregional quantification of the BR-163 corridor

### 3.3 Comparison of the subregional dynamics along the BR-163 corridor between the coupled and noncoupled model quantifications

The *Trend* scenario: The main difference between the two quantification approaches manifested in different cropland change dynamics. The subregional quantification estimated a stronger expansion of cropland than did the coupled quantification (Figure IV-4c). We found an increase in cropland of more than 5% along the BR-163 corridor until 2030 following the subregional trend extrapolation compared with a reduction of 0.3% estimated from the coupled approach. Land allocated for pasture increased in both approaches, though the increase was stronger in the subregional quantified scenario. In 2030, the estimated

pasture increase differed by only 2%. Urban areas along the BR-163 were estimated to expand in the subregionally quantified scenarios (by 0.2%) but not in the coupled approach.

The *Sustainable Development* scenario: The subregional quantification of the *Sustainable Development* scenario resulted in an extensive reduction of pastureland (Figure IV-4d). This was caused by the assumptions of a 70% reduction of livestock by 2030 compared with the *Trend* scenario. Cropland expansion along the BR-163 was greater with the coupled quantification approach. Cropland expanded by roughly 6% compared with a 1% increase for the subregional quantification. Urban area increased by 0.1% for the subregional quantification.

### 3.4 Spatial explicit land use change and deforestation estimates

We iteratively calibrated the subregional land use model based on two available land use classifications, the 2010 and 2014 TerraClass. During the calibration, we adjusted the model elasticities based on the cross-tabulated error matrix of all observations. The overall accuracy of the modeled land use change map, compared with the “true” land use change map, reached 91%.

Estimates of deforestation along the BR-163 between 2010 and 2030 differed substantially between the scenarios and between the quantification approaches. The subregional quantification of the *Trend* scenario resulted in nearly double the amount of deforestation of that in the coupled approach (Figure IV-5a: 7,250 km<sup>2</sup>, coupled; 13,207 km<sup>2</sup>, subregional). The *Sustainable Development* scenario quantified at the subregional level resulted in the lowest deforestation rates (Figure IV-5b: 1.5 km<sup>2</sup>). The coupled *Sustainable Development* scenarios had lower deforestation rates than those in the *Trend* scenario but higher rates than in the subregional quantification (Figure IV-5b: 213 km<sup>2</sup>, coupled).

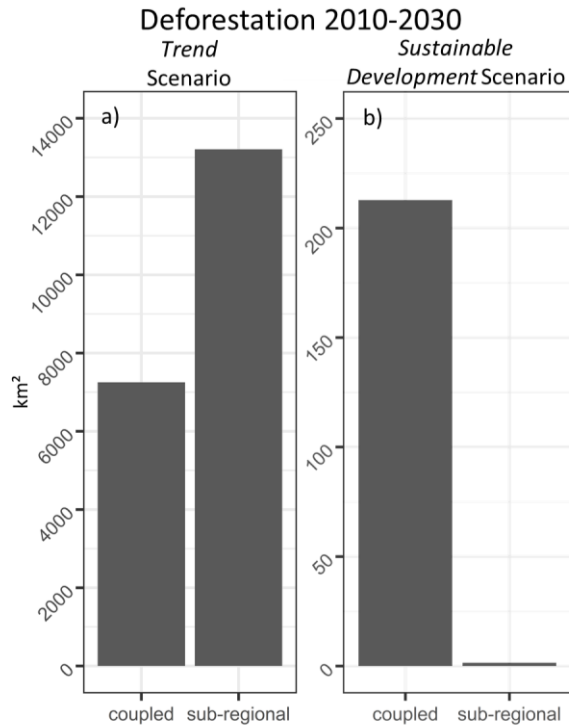


Figure IV-5: Deforestation in kilometer squared according to the different scenarios and quantification approaches within the BR-163 corridor

The spatial allocation of land use change followed the historic expansion patterns (Figure IV-6). Cropland expanded in the south of the study region, pasture in the center and north, and urban areas around the current urban centers. The *Trend* scenario indicated tremendous pressure on the conversion of land by converting the last remnants of natural vegetation in the south and center of the study region to either crop or pasture. The pasture expansion hot spots were simulated to stretch along the highway around Novo Progresso and in the north of MT. Secondary vegetation is most likely to occur in the area between Sinop and Guarantã do Norte and in distant areas away from the BR-163 highway in PA.

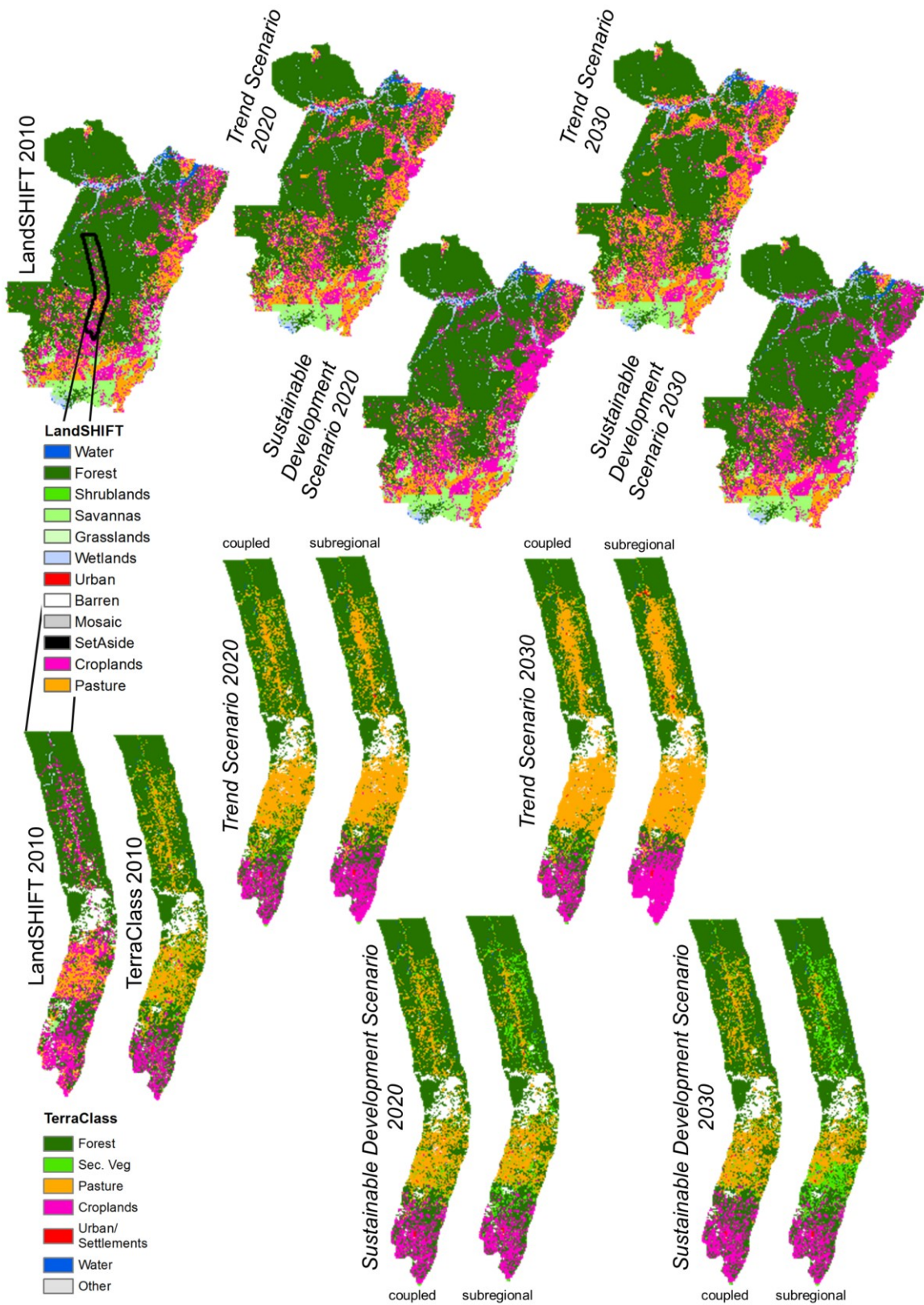


Figure IV-6: Spatial representation of the Trend and Sustainable Development land use change scenarios in 10-year intervals; regional scenarios covering MT and PA (top) and the two quantification approaches at the subregional scale along the BR-163 corridor (bottom)



#### 4 Discussion

In this study, we analyzed the differences in two land use change scenarios between using coupled and noncoupled scenario quantification approaches. The coupled approach combined two land use models that ran at different scales. The LandSHIFT modeled land use for the whole of the states of MT and PA and was coupled to alucR, which simulated land use dynamics for a subset of these states along the BR-163 highway. We compared the coupled model results with those from using noncoupled subregional quantification for the BR-163 corridor.

We partly expanded earlier approaches of coupled land use change assessments to take advantage of different land use maps available at different scales. Whereas earlier approaches assessed land use changes across scales to improve the local understanding of processes, they used the same land use maps at different aggregation levels. However, from regional to global scales, explicit spatial land use information often relies on global assessments of land use and cover (e.g., MODIS, GLC-2000, and GlobCover), which have been identified to have inappropriate accuracies for regional assessments (Fritz et al., 2011). Because inaccuracies in the land use and cover distribution can be expected to persist throughout the scenario development, we argue that the reliability of scenario results crucially depends on the regional accuracy of the initial land use data. Additionally, the detailed and official character of TerraClass 2010 gives the classifications high credibility for subregional assessments (INPE, 2015). Still, one could argue for the use of TerraClass 2010 for both the regional (LandSHIFT) and subregional (alucR) models. The limited spatial extent of TerraClass 2010, defined by the boundaries of the Amazon biome, did not cover the full extent of MT, which made it impossible to use for LandSHIFT under the current modeling setup.

Differences in land use and cover that affected the coupled scenario assessment between scales related to the amounts and spatial locations. The comparison indicated large differences between land use and cover for the year 2010, mostly related to confusion between cropland and pasture and to disagreements in the amounts of urban land. In the north of the study area, land in TerraClass 2010 was dominated by pasture, whereas LandSHIFT 2010 allocated a considerable amount to cropland. This is likely attributable to the spectral similarity between pasture and cropland, which led to class confusions based on the MODIS land cover classifications. Urban area differences may relate to the large

difference in spatial resolution, and coupling the scenario analysis can increase the spatial representation of land uses at the subregional scale compared with regional scenario results.

We adapted the coupling procedure from earlier studies (Verburg et al., 1999; Moreira et al., 2008). Rather than passing the total amount of land use from one model to the other, we coupled the amount of change. This adaptation was necessary because of the differences between the two land use maps. We could argue that coupling the amount of change in land use from the regional to the subregional scale preserves the advantages of scenario consistency between scales (i.e., captures land use dynamics between scales), while at the same time it sustains the accuracy of the subregional land use map. Summarized, the advantage of cross-scale modeling is that it improves the legitimacy (improved spatial representation of land uses at the subregional level) and consistency (land use dynamics are consistent from the regional to the subregional scale) of the scenario results for large-scale analysis, which provides more accurate details at the subregional scale.

The coupled approach is capable of capturing processes of land use displacement (e.g., conversions of pasture to cropland leading to pasture expansion elsewhere) that can affect deforestation or similar land use changes within a subregion (Lapola et al., 2010a; Arima et al., 2011; Gollnow and Lakes, 2014). Accordingly, displacement passed from the regional to the subregional scale in theory leads to greater land use changes (pasture expansion) in the coupled scenario quantification. Partly contradictive to our expectation, the analysis did not indicate stronger land use change dynamics derived from the coupled quantification approach. Instead, the subregional quantification in the *Trend* scenario led to the highest land use change rate. This can be explained by the quantification process, specifically the extrapolation of past trends. Displacement effects were already captured within the subregional quantification because the municipality statistics used for extrapolation included those dynamics within the time series (Lapola et al., 2010a; Arima et al., 2011; Gollnow and Lakes, 2014). Considering this, we recommend taking advantage of multiscale modeling when cross-scale land use processes (e.g., indirect land use changes) are expected to change from previous developments and are not yet captured in a subregional trend.

The coupled *Trend* scenario highlights the BR-163 region to experience further pasture expansion. Cropland expands more in other regions of MT and PA than along the BR-163 corridor, and similarly, urban expansion is not likely to occur along the highway. The subregional quantification of the *Trend* scenario was similarly dominated by the expansion of pastures along the highway. Additionally, both cropland and urban areas expanded, which

led to the highest deforestation rates. These trends portray the recent dynamics along the BR-163, shaped by land use intensification, expansion of export-oriented crops, and increasing land prices (Rudorff et al., 2011; Richards, 2012b). However, the latest dynamics within the region, the implementation of land use policies such as the PPCDAm, and agricultural prices have slowed the expansion of cropland and pasture (Macedo et al., 2012; Gollnow and Lakes, 2014; Gibbs et al., 2015).

The *Sustainable Development* scenario was quantified by adjusting the trend scenario toward global and regional changes in diet, decreasing cattle production, and enforcing spatial policies (e.g., for protected areas, indigenous lands, sustainable use areas, and military areas). The results from the coupled *Sustainable Development* scenario highlight different land use change intensities between the BR-163 corridor and the states of MT and PA, although both experienced decreases in pasture and increases in cropland. The change rates for all of MT and PA were double those along the BR-163. The BR-163 region continues to be characterized by pastureland. The subregional quantification resulted in a drastic reduction of pastures with a small increase in cropland. Distinct from the other scenarios, secondary vegetation increased in former pasture areas, especially in PA and between Sinop and Guarantã do Norte (MT). These differences between the two quantification approaches stress the importance of scale for scenario quantification.

On the one hand, the scenario analysis identified the BR-163 corridor as one of the regions in MT and PA that is especially prone to further pasture expansion. On the other hand, cropland expansion was more likely in other regions of MT and PA than along the BR-163 corridor and may be a smaller thread to deforestation than increased cattle production. Within the corridor, cropland was more likely to expand in the south of the study region along the BR-163, where relief, precipitation, and infrastructure are more favorable. Pasture expansion, in contrast, was determined by infrastructure availability or accessibility and appeared to be indifferent to biophysical determinants (Table SI IV-7). Using this rationale, effectively implementing the Beef Moratorium and completing the CAR combined with intensification efforts can be important for curbing deforestation in the region, next to the notably successful implementation of the Soy Moratorium and the strategies implemented in the PPCDAm.

The variation of deforestation under the different scenarios and quantification approaches stresses the scale dependency and uncertainties involved in spatially explicit scenario analyses. The highest deforestation estimates were calculated for the subregional

quantification of the *Trend* scenarios. To reduce deforestation, it will be critical to find pathways toward more sustainable development at the global, regional, and subregional scales (Aguiar et al., 2016).

## 5 Conclusion

This study provided scenarios of land use change along the BR-163 highway in the Brazilian Amazon by comparing a multiscale model coupling approach with a conventional subregional scenario quantification. We found large differences between the scenarios and the quantification approaches, which emphasizes the importance of scale and uncertainties in scenario quantification.

We found that combining coarse- and high-resolution land use data across spatial scales provided high spatial detail at the subregional level while accounting for land use changes across scales. On the contrary, subregional model quantification may be superior in capturing locally specific dynamics. However, the limited extent of the subregional model could make it prone to overpredicting land use changes because all changes are restricted to the defined boundaries.

Beyond the above-mentioned considerations, we believe that by applying land use maps of different resolutions, each adequate for the spatial scales involved, we increased the credibility of the spatially explicit scenarios for the subregional level compared with the results of large-scale scenario models. This is especially true for cases in which high-resolution spatial maps are not available for use as inputs in large-scale models but are available for subsets of the area of interest.

Overall, the scenarios identify the region along the BR-163 as likely to experience additional pasture expansion. This underlines the importance of policies to curb deforestation, strengthen the efforts to implement the Beef Moratorium, complete the CAR, alongside the notably successful implementation of the Soy Moratorium and the PPCDAm's environmental monitoring and expansion of the protected areas network.

### **Acknowledgements**

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## Supplementary Information

Table SI IV-1: alucR elasticities matrix (iteratively derived by increasing the overall accuracy of the model)

From\To	1	2	3	4	5	6	7
1 Forest	0.3	0	0.25	0	0	0	0.3
2 Sec. Veg	0	0.05	0.1	0.2	0.2	0	0.1
3 Pasture	0	0	0.95	0.5	0	0	0.8
4 Cropland	0	0	0.2	1	0	0	0.9
5 Urban	0	0	0	0	1	0	0
6 Water	0	0	0	0	0	0	0
7 Other	0	0	0	0	0	0	1

Table SI IV-2: 3 alucR trajectories matrix (years before conversion of land use is allowed; 0: no conversion; 1: conversion after one year allowed; 70: conversion after 70 years allowed)

From\To	1	2	3	4	5	6	7
1 Forest	1	0	0	0	1	0	0
2 Sec. Veg	70	1	1	1	1	0	0
3 Pasture	0	1	1	1	1	0	0
4 Cropland	0	1	1	1	1	0	0
5 Urban	0	1	1	1	1	0	0
6 Water	0	0	0	0	0	0	0
7 Other	0	0	0	0	0	0	0

Table SI IV-3: Crop-types and livestock data (source: IBGE, 2013, 2016)

Crop-types for scenario quantification (ha & tons)	Livestock data (head)
Cassava	Cattle
Tobacco, coffee, cacao (default crops)	Goats
Beans (pulses)	Sheep
Cotton	
Banana, orange, grape (subtropical fruits)	
Groundnut	
Maize	
Rice	
Soybean	
Sugarcane	
Tomato, onion, potato (vegetables)	
Wheat	

Table SI IV-4: Spatial information for the scenario quantification (source: IBGE, 2013, 2016)

<b>Coupled modeling approach (LandSHIFT/alucR)</b>	<b>BR-163 scenario quantification (alucR)</b>
We quantified and run the scenarios for Mato Grosso (MT) and Pará (PA) state. We then extracted the land use changes within the 100km buffer along the BR-163, as describes in Figure IV-2	<p>Scenarios were quantified based on census data referring to the following municipalities in Mato Grosso (MT) and Pará (PA) state:</p> <ul style="list-style-type: none"> <li>• Novo Progresso, PA</li> <li>• Itaituba, PA</li> <li>• Altamira, PA</li> <li>• Novo Mundo, MT</li> <li>• Guarantá do Norte, MT</li> <li>• Matupa, MT</li> <li>• Novo Guarita, MT</li> <li>• Peixoto de Azevedo, MT</li> <li>• Terra Nova do Norte, MT</li> <li>• Colider, MT</li> <li>• Nova Santa Helena, MT</li> <li>• Itauba, MT</li> <li>• Claudia, MT</li> <li>• Ipiranga do Norte, MT</li> <li>• Sinop, MT</li> <li>• Santa Carmen, MT</li> <li>• Vera, MT</li> </ul>

Table SI IV-5: Land use and cover harmonization between LandSHIFT 2010 (based on MODIS) and TerraClass 2010 (source: GLCF (2014) MODIS Land Cover. MCD12Q1. <http://glcf.umd.edu/data/lc/> ; INPE (2015) Projecto TerraClass. [http://www.inpe.br/cra/projetos\\_pesquisas/dados\\_terraclass.php](http://www.inpe.br/cra/projetos_pesquisas/dados_terraclass.php))

<b>LandSHIFT (MODIS)</b>	<b>Harmonized classes</b>	<b>TerraClass</b>
Water	Water	Water
Evergreen needleleaf forests	Forest	Forest
Evergreen broadleaf forests		
Deciduous needleleaf forests		
Deciduous broadleaf forests		
Mixed forests		
Closed shrublands	Secondary vegetation	Secondary forest
Open shrublands		
Woody savannas		
Savannas		
Grasslands		
Permanent wetlands	Water	Water
Cropland	Cropland	Cropland
Urban and built-up	Urban	Urban
Cropland/natural vegetation mosaics	Cropland	Mosaic of occupation (mosaico de ocupações)

Snow and ice	Other	No forest		
Barren		Other		
		Forest plantation		
Water bodies	Water	Water		
Mosaic	Cropland	Mosaic of occupation (mosaico de ocupações)		
Set aside	Secondary vegetation	Secondary forest		
Default crops	Cropland	Cropland		
Cassava				
Temperate cereals				
Tropical cereals				
Cotton				
Fruits				
Groundnuts				
Maize				
Millet				
Annual oil crops				
Permanent oil crops				
Pulses				
Rice				
Temperate roots and tubers				
Tropical roots and tubers				
Sorghum				
Soybeans				
Stimulants			Cropland	Cropland
Sugarcane				
Vegetables				
Wheat				
Pasture	Pasture	Pasture (pasto limpo)		
Rangeland		Pasture with bushes (pasto sujo)		
Grazing land		Secondary forest with pasture		



Scenarios of land use change in a deforestation corridor in the Brazilian Amazon:  
combining two scales of analysis

Table SI IV-6: Scenario story lines

<i>Trend</i>	<i>Sustainable Development</i>
<p><b>Cenário básico:</b> Crescimento da demanda por produtos agrícolas continua, se convertem ecossistemas naturais, se asfalta a BR-163, há a tendência da intensificação da produção agrícola, mudanças climáticas resultantes do cenário RCP, similar ao A1B.</p> <p><b>Dados de entrada:</b> desenvolvimento demográfico, produção agrícola, produção pecuária, política ambiental e agrária, áreas de proteção, infraestrutura, capacidade de adaptação aos efeitos das mudanças climáticas</p>	<p><b>Cenário Sustentável 2030:</b> Também este cenário, por imaginativo que seja, é orientado pelas possibilidades que, de acordo com o conhecimento dos participantes da oficina, são julgados como realísticos, embora se supõe que não se realizem de fato.</p> <p>O cenário é baseado nos seguintes fatores de sustentabilidade: participação; cidadania (com possibilidade de reivindicação!); implementação das leis inclusive legislação adequada; sistema econômico incluyente; soberania de alimentação; proteção de recursos com monitoramento participativo; vontade política para o desenvolvimento local, incluyente e sustentável beneficiando a maioria da população; conhecimento e soluções tecnológicas disponíveis; a qualidade da crescente demanda por bens agrários (ex.: demanda crescente por bens certificados); fomento financeiro internacional para a economia sustentável; identificação com a região e identidade regional; fomento da cadeias de agregação de valor; diversidade e resiliência; assistência e consultoria agrária alternativa; solução da questão de direitos de posse/ reforma.</p> <p><b>Dados de entrada:</b> desenvolvimento demográfico, produção agrícola, produção pecuária, política ambiental e agrária, áreas de proteção, infraestrutura, capacidade de adaptação aos efeitos das mudanças climática</p>
<p><b>Desenvolvimento demográfico</b></p> <p>A demanda crescente por produtos agrícolas no mercado mundial resulta numa maior pressão sobre recursos naturais, inclusive a terra. Isso acarreta o aumento da eficiência produtiva pelo maior nível de mecanização e consequentemente menor intensidade de trabalho na produção agrícola. Também causa a expansão de monoculturas e a concentração da terra no setor agrário, tendo como consequência a deslocação forçada contínua de trabalhadores rurais, agricultores familiares e pecuaristas de menor eficiência econômica. Uma parte dos deslocados encontrará trabalho nas novas aglomerações urbanas ao longo da BR-163, enquanto outros seguirão ao Norte da região, adiando a conversão de floresta em pasto e lavoura na Amazônia. Em geral, se observe um crescimento de centros urbanos regionais. Por consequência, se amplia o setor terciário. Essas cidades jovens apresentam configurações rural-urbanas específicas: muitas vezes os produtores agrários possuem residência na área urbana, dissolvendo assim a divisão clássica entre o meio urbano e o meio rural. Ao mesmo tempo, as tensões sociais aumentam por causa da deslocação forçada e da proletarização crescente, e o Estado não dispõe das capacidades institucionais e financeiras para equilibrá-las. O Plano do Desenvolvimento Sustentável da BR-163 sumiu nas gavetas em Brasília, fato pelo qual a população local não guarde boas memórias de processos participativos. A resistência das pragas sobe, resultando no maior risco de perdas na safra, o que se visa amenizar com um maior uso de agrotóxicos. Isso incrementa os efeitos negativos à saúde da população local. Mesmo tendo acesso à internet, no Pará prevalece a circulação do conhecimento de boca em boca, enquanto no Mato Grosso a circulação é realizado pelos numerosos serviços de informação agrária, respetivo via internet. Os meios de comunicação clássicos empenham um papel pouco relevante na região. Expandem-se facultades que oferecem disciplinas relevantes para o uso de terra ao longo da BR-163.</p>	<p><b>Desenvolvimento demográfico</b></p> <p>Um mudança básica teve lugar na região da BR-163, resultando numa cultura política democrática. Principalmente no Pará, mas também no Mato Grosso, realizam-se processos participativos e uma troca deliberativa de opiniões. Predomina um clima que combina os princípios do estado de direito e a segurança na implementação das leis. As instituições e poderes governamentais prestam contas entre elas a à população (Accountability). A formação da vontade política é tão transparente como os processos governamentais, utilizando instrumentos como o orçamento participativo. respeita-se o salário mínimo, e as rendas mais altas se limitam por mudanças nas taxas de imposto. Apesar de não haver tanta demanda por transferências governamentais porque o sistema econômico é mais justo, a população necessitada tem acesso aos programas de Bolsa Família e Minha Casa Minha Vida. A gama dos programas governamentais se complementa com o pagamento de serviços ambientais. As instituições estatais são melhor abastecidas e as organizações da sociedade civil são fortalecidas, o que abre oportunidades diversificadas de educação, oportunidades de trabalho e novas perspectivas para a população. A migração para a região pode crescer devido ao clima social favorável. Como não haverá migração por causa de deslocamento forçado, resultado de fatores socio-econômicos, a necessidade da migração inter-regional deixa de existir. No lugar deste tipo de migração, observa-se a migração inter-regional de profissionais e uma migração intra-regional equilibrada, ocasionado pela atração crescente das cidades médias. complementa-se o cenário pelo crescimento endógeno do espaço urbano e assim a estabilização da classe média urbana, que continua defendendo a sustentabilidade e justiça rural e urbana. As oportunidades de sobrevivência nas áreas rurais crescem e assim, o problema do êxodo rural é amenizado. Uma melhor circulação de conhecimento leva a um melhor planejamento das atividades econômicas, promovendo estratégias como a agricultura de baixo insumos (low-input agriculture) e diversifica as oportunidades de geração de renda. Assim, criam-se oportunidades de geração de renda independentes da terra no setor de serviços. Deste modo, os mercados regionais e locais de trabalho alinham-se com a nova estratégia de desenvolvimento. E as necessidades dos mercados de trabalho, sendo conhecimento e consultoria, assim como as necessidades de investimento e logística, são satisfeitas pelas instituições responsáveis. Também o apoio à pesquisa científica aplicada, como o fomento da indústria baseada em produtos florestais não madeireiros, fazem parte dessa estratégia de desenvolvimento. A BR-163 é conhecida como região no processo de aprendizagem contínuo que valoriza as diferentes formas de conhecimento. Em numerosos centros nacionais de educação, os quais promovem a aprendizagem entre iguais (peer learning), fortalece-se a coesão sócio-cultural da população. Os centros de educação aproveitam práticas bem sucedidas da transmissão de conhecimento da indústria (SENAI/SENAC), da agricultura (SENAR) e dos empreendedores (SEBRAE). As redes sociais possuem um efeito positivo para a formação de redes cooperativas de produção e comercialização, as quais promovem sistemas de produção sustentáveis, diversificados e marcados pela autodeterminação dos seus participantes. Essas redes são capazes de amenizar as consequências negativas das mudanças climáticas. realiza-se um ordenamento territorial adaptado às necessidades da região. Portanto, a população se concentra nas áreas adequadas para a colonização e, tanto as áreas de terra Branca, como as áreas ainda inexploradas, não são colonizadas.</p>
<p><b>Produção agrícola</b></p> <p>A estrutura da produção agrícola varia ao longo da rodovia de 1.780 km: no Mato Grosso, a dependência de multinacionais agrárias, a qual restringe as margens para decisões de inovação por causas econômicas, cresce proporcionalmente com a capitalização e as monoculturas (soja, milho, algodão). Dependendo do destino da exportação, se requiere a observação de padrões higiênicos estritos em relação a separação de sementes geneticamente modificados de sementes não modificados. Isso se torna complicado por capacidades de armazenagem insuficientes nos portos de exportação e na região produtora. Deste modo, crescem os problemas do cumprimento com a padronização e com a higiene OGM, o que pode causar quedas na venda da</p>	<p><b>Produção agrícola</b></p> <p>A implementação de um planejamento territorial que visa a sustentabilidade local e regional resulta numa produção agrária diversificada. O zoneamento no contexto desse planejamento assegura a satisfação da demanda doméstica e limita as possibilidades de gerar divisas nos mercados de exportação. limitam-se as possibilidades da expansão da agricultura comercial pelo ordenamento territorial e pela inclusão dos custos de frete na formação de preços na produção de alimentos. Deste modo, modificam-se os ciclos econômicos, tanto exógeno- como endogenamente. estabiliza-se a economia na região da BR-163 por várias redes de agregação de valor no nível local e regional que se destacam pelo beneficiamento diferenciado dos produtos, entre eles os produtos florestais não-madeireiros, os sistemas agroflorestais, a piscicultura, o artesanato, a economia madeireira e de caça sustentável, e o ecoturismo. A produção agrícola se orienta no princípio da soberania</p>

<p>produção agrícola. O crescimento do setor agrário no Mato Grosso não é limitado pela falta de terra, e sim pela infraestrutura e capacidades de armazenamento, o que constituem o calcanhar de Aquiles da agropecuária na região. No Pará, a estrutura agrária é marcada pelo aumento de gado em criação extensiva e por estruturas monopolizadas no processamento da produção. Assim, os migrantes oriundos da agricultura familiar são deslocados para o norte do Pará, enquanto no sul da BR-163, se amplia o uso de tecnologia na lavoura de soja, o que desloca a pecuária bovina para o Norte. Na área dos portos de exportação (Santarém e Miritituba) o plantio de culturas destinadas a exportação continua expandindo-se.</p>	<p>alimentar e assim fortalece a agricultura familiar e os mercados locais. Há um fomento forte da agricultura familiar para suprir os mercados locais: reservam-se áreas para a produção regional e local de alimentos, apoia-se a comercialização local, e fortalecem-se os ciclos econômicos regionais</p> <p>A médio prazo, essas medidas resultam numa maior arrecadação de impostos, que financia o desenvolvimento regional sustentável. Já que a exportação não é mais o principal estruturador da economia, consegue-se implementar uma zona de produção agrícola que está livre de organismos geneticamente modificados, e estabelecem-se novas estratégias para a o uso reduzido de fertilizantes e agrotóxicos (sistemas de rotação, mixed crop, sistemas misturados). Onde foi possível, uma agricultura conservadora de baixos insumos (low-input conservation agriculture) foi estabelecida. O acesso ao conhecimento para produtores agrários é melhorado pela distribuição mais consciente do conhecimento. A expansão da produção é garantida pela intensificação da produtividade de áreas ao invés da produtividade de trabalho, integrando assim mais mão de obra.</p> <p>O papel de uma demanda que exige sustentabilidade ficou mais importante, assim, as moratórias de soja e de carne bovina, com respeito às exigências para a produção sustentável, são bem consolidadas, e os clientes as respeitam, seguindo a tendência global para um consumo de produtos sustentáveis. Na política local, ademanda externa e os efeitos dela são bem administrados. As distorções de preços no mercado mundial por subvenções (algodão, milho, leite...) se reduziram gradualmente; os produtos não certificados quase não encontram demanda, e as quotas de mercado para produtos ecológicamente produzidos aumentam, por exemplo para soja, carne e óleo de dendê. Incentivados pela estrutura da demanda, que visa a sustentabilidade, os mercados se adaptaram amplamente às formas agroecológicas de produção.</p>
<p><u>Produção Pecuária</u></p> <p>Como não há epidemias de animais, se incrementa a produção de carne na região inteira, sobretudo de carne bovina. No Mato Grosso, cresce a criação intensiva. Isso resulta no maior uso e na poluição d'água. Na região inteira, se reformam e aproveitam mais e mais pastos degradados, mesmo assim continua a transformação de floresta em pasto. Isso é motivado especialmente pela especulação de terra e preços crescentes da terra. O crescimento da produção de carne resulta na concentração de terra e poder econômico (a qual pode se manifestar também em poder político) mencionado acima, e num incremento das relações de trabalho precárias no meio rural e nos matadouros e frigoríficos legais e ilegais.</p>	<p><u>Produção pecuária</u></p> <p>De acordo com as apresentações acima, a população de gado é menor que nos outros cenários, por restrições impostas, assim como queda na demanda devido às mudanças nos hábitos alimentares. O fortalecimento dos mercados regionais resulta numa expansão da pecuária leiteira. A expansão de sistemas agroflorestais sobre pastagens (degradadas) reduz as formas de criação extensivas e moderadamente produtivas, e leva à intensificação das pastagens em sistemas de rotação. Assim, a silvicultura, a lavoura e as pastagens se alternam ou são parcialmente integradas. Deste modo, podem-se aproveitar efeitos sinérgicos, e a diversificação da produção reduz a vulnerabilidade frente a choques externos. Em algumas áreas, cria-se o boi verde, ou seja, gado que somente se alimenta de pasto e cuja criação segue critérios ecológicos e é habilmente comercializado. Na avaliação da sustentabilidade da produção pecuária, consideram-se critérios como a concorrência de áreas de produção, assim como o balanço de dióxido de carbono, entre outros fatores relevantes.</p>
<p><u>Política Ambiental e Agrária</u></p> <p>A política agrária e ambiental é fortemente marcada pela situação e pela conjuntura política respectiva, e assim se mostra inconsistente e intransparente. Especialmente a política ambiental consiste de medidas pontuais e drásticas visando a redução de efeitos negativos, mas sem um planejamento integrado ao longo prazo e continua com brechas. Isso se complementa pelo fato de que as instituições estatais e federais só terem uma limitada capacidade de implementação. A alta impunidade e a falta de respeito frente a lei escrita enfraquecem a soberania do Estado e sua credibilidade na regulação. A política agrária visa principalmente o aumento da produção destinada à exportação e o fomento de produtores grandes e capitalizados. Ela não integra a questão ambiental em suas estratégias e dá maior prioridade aos interesses da agropecuária destinada a exportação quando estão em conflito com as políticas ambiental e climática. Os produtores da agricultura familiar são afetados de forma negativa pela política agrária e ambiental e tratam de sobreviver em nichos.</p> <p>Por causa da inconsistência da regulação estatal nas questões ambientais e da forte dependência do mercado mundial, os produtores médios e pecuaristas dificilmente podem planejar suas atividades e desenvolvem estratégias de sobrevivência de curto a médio prazo. Se pode identificar uma presença crescente de instrumentos da política ambiental e climática e os programas respetivos de desenvolvimento regional: programas como o Cadastro Ambiental Rural proporcionam potencialmente o monitoramento e a sanção agrária e ambiental dos fazendeiros, mas seus efeitos estruturais ainda não se podem avaliar. De forma crescente, esse instrumento se aplica na comercialização, inclusive nos mercados internacionais, o que incentiva a sua implementação.</p>	<p><u>Política agrária e ambiental</u></p> <p>Como a política agrária e ambiental são desenvolvidas e negociadas de forma democrática, observa-se um diálogo intensivo entre os dois setores da política que integra a participação da população local. A implementação da política ambiental beneficiando o meio ambiente e também os seres humanos é somente possível quando baseada nesse equilíbrio entre os dois setores, o qual considera o urbano e o rural como um sistema integrado.</p> <p>realizou-se uma reforma agrária ecológica por meio de um ordenamento e planejamento territorial racional e participativo, respeitando a questão da redistribuição de recursos. Deste modo, foi possível evitar uma reforma agrária em larga escala, que está fortemente carregada de ideologia no Brasil.</p> <p>De um modo geral, as melhoras no nível de conhecimento da população local, a transparência das ações políticas assim como a prestação de contas por parte dos políticos aumentaram a confiança nos sistemas de governança e reduziram os custos de transação dos processos de participação, depois de um período de treinamento.</p> <p>A implementação geral de um imposto sobre a propriedade imobiliária, o fomento de certificações e de proteção de florestas por sistemas de incentivos, assim como a assistência técnica para produtores pequenos em questões agroecológicas dentro e fora de assentamentos, contribuíram para a diversificação da agricultura e da integração de agro-silvicultura e fortaleceram e difundiram o sistema de agricultura familiar. Na região inteira, movimentos sociais representam os interesses dos pequenos produtores e atraem numerosos projetos REDD.</p> <p>Em geral, podia-se integrar melhor a perspectiva regional às políticas. O enfoque local predomina sobre o enfoque regional: sistemas locais de governança que se baseiam em caminhos de desenvolvimento adequados à realidade local predominam e se complementam por uma implementação mais forte da legislação e por pagamentos compensatórios para REDD e reflorestamento.</p>
<p><u>Áreas de proteção</u></p> <p>Existem numerosas áreas de proteção no Pará e no Mato Grosso, mas com uma administração deficiente, e raramente com monitoramento participativo. Mesmo assim, jogam um papel importante na preservação de recursos naturais e da terra. Os zoneamentos no nível macro, a falta de implementação da lei e a falta de recursos nos órgãos de fiscalização, juntos à pressão crescente sobre a terra, resultam no fato de que as reivindicações de justiça social contribuem para a diminuição das áreas de</p>	<p><u>Áreas de proteção</u></p> <p>No contexto do zoneamento todas as categorias de proteção foram revisadas, resultando em um consenso em relação à preservação de áreas de proteção existentes e à não exploração de áreas florestais. Isso resulta numa legislação de não exploração, incluindo o fomento às alternativas econômicas e pagamentos compensatórios. Esses pagamentos, assim como o apoio de um manejo de carbono, são assegurados por pagamentos de transferência no nível nacional e internacional. A população local participa na definição, no monitoramento e na administração das áreas de proteção, levando à maior aceitação e sustentabilidade das áreas protegidas.</p>

Scenarios of land use change in a deforestation corridor in the Brazilian Amazon:  
combining two scales of analysis

<p>proteção. Projetos estatais de infraestrutura, inclusive barragens, ameaçam áreas de proteção existentes e em formação.</p>	<p>Em cooperação com os povos indígenas ali residentes, leva-se adiante o desenvolvimento de estratégias de uso sustentável das áreas de proteção, por exemplo em consultas que se baseiam na nova legislação em relação à consulta prévia. Devido ao fato que muitos indígenas vivem, pelo menos parcialmente, na cidade, é importante a consideração das cidades próximas às áreas de proteção nesse processo. As cidades de médio porte podem integrar essas estratégias através da infraestrutura social, oferecendo educação, conhecimento, créditos e saúde, ampliando as oportunidades e o acesso da população residentes nas áreas de proteção. Ainda, as áreas de proteção próximas às cidades podem, através de trilhas educativas sobre as relações entre diversidade ecológica e cultural e através de oportunidades de ecoturismo, contribuir para a consciência sobre relações sustentáveis entre homem e natureza.</p> <p>Adicionalmente, as condições de uso para as áreas protegidas, por exemplo nas reservas extrativistas, ampliaram-se de tal forma que as comunidades tradicionais ali residentes podem viver realmente as formas de uso prescritas. Na ampliação das formas de uso, inclui-se, entre outros, o apoio aos sistemas agroflorestais, ao ecoturismo e às formas tradicionais de alimentação.</p>
<p><u>Infraestrutura</u></p> <p>Como o asfaltamento da BR-163 se demora já por anos, a população local vive em constante espera e frustração em relação a oportunidades melhoradas de escoamento e mobilidade. Mesmo assim, é provável que se completará o asfaltamento no contexto do IIRSA. Em paralelo, se procura alternativas logísticas para a exportação, como a Hidrovia Teles Pires e a Ferrovia Rondonópolis-Cuiabá-Santarém, que beneficiariam principalmente o setor agrário de Mato Grosso.</p>	<p><u>Infraestrutura</u></p> <p>O conceito de infraestrutura é amplo e diversificado, significando a ampliação e proteção da infraestrutura social, econômica e ecológica que visa a conciliação dos objetivos sociais, econômicos e ecológicos. Isso inclui investimentos públicos suficientes numa infraestrutura ecológica e social, estabelecendo para o longo prazo sistemas de saúde, de educação e formação e centros descentralizados de abastecimento, assim como sistemas descentralizados de energia e rodovias. Como é orientada pelo desenvolvimento sustentável, ampliam-se sobretudo as estruturas locais de comercialização. fomenta-se a infraestrutura no conceito clássico de modo equilibrado para a exportação e para a mobilidade regional. O Estado e a sociedade civil alavancam o estabelecimento de centros de inovações, por exemplo para produtos florestais não madeireiros e indústria farmacêutica.</p> <p>Como o desenvolvimento da região é determinado de forma participativa, também é normal a participação da população local nos projetos de infraestrutura. Já que nunca se podem evitar conflitos na conciliação de objetivos sociais, econômicos e ecológicos, investiu-se na ampliação de sistemas de comunicação e informação para melhorar a representação informada dos diferentes interesses. Por exemplo, existe uma discussão transparente sobre a desistência de uma exploração avançada de áreas escassamente colonizadas, tratando também da questão sobre quais áreas se deveria levar adiante a colonização. Dessa forma, pode-se abertamente discutir sobre vários assuntos conflitivos: a contradição entre o direito ao acesso à infraestrutura e a proteção ambiental e a questão de quem assumiria os custos de oportunidade da proteção ambiental.</p>
<p><u>Capacidade de adaptação aos efeitos das mudanças climáticas</u></p> <p>Como efeitos das mudanças climáticas, se percebem secas periódicas. A escassez de água se agrava pela qualidade reduzida da água devido à concentração crescente de agrotóxicos e fertilizantes. Oscilações na precipitação constituem um perigo para usinas hidrelétricas e as hidrovias planejadas porque seriam temporalmente inutilizáveis. A ocorrência de eventos climáticos extremos como ondas de calor e precipitações extremas põem em perigo as plantações, o armazenamento e o transporte dos bens agrários, intensificam os efeitos negativos sobre a saúde da população local e ameaçam a biodiversidade com riscos imprevisíveis. O controle de incêndios se mostra cada vez mais difícil.</p> <p>Contudo, se pode dizer que em geral, tanto no Pará quanto no Mato Grosso, prevalece uma perspectiva otimista em relação ao desenvolvimento passado e futuro da região, mesmo que o gerenciamento de inseguridades em muitas áreas da vida seja uma parte substancial das estratégias de sobrevivência na BR-163. O boom de carne e soja proporciona um bem-estar crescente, mas mal distribuído na região toda. Sinal disso é a organização particular de estruturas de infraestrutura e serviços que se dá em muitos lugares. Vale ressaltar que por causa da alta dependência do mercado mundial dos setores carne e soja, os mercados regionais e os ganhos no bem-estar e investimentos relacionados ficam limitados e vulneráveis.</p>	<p><u>Capacidade de adaptação aos efeitos da mudança climáticas</u></p> <p>A estabilidade dos sistemas sociais (resiliência) compensa as incertezas e a vulnerabilidade incrementada frente aos efeitos das mudanças climáticas em boa parte, de modo que os efeitos das mudanças climáticas transmitidos socialmente se reduzem. Em virtude das muitas discussões sobre o desenvolvimento sustentável, cresceu-se a consciência sobre as mudanças climáticas, a qual acelera a perseguição de caminhos alternativos de desenvolvimento. A elaboração local e participativa de estratégias de mitigação e adaptação contribuiu para a decisão sobre opções de produção agroecológicas. A colaboração social, as estruturas fortes de fomento e apoio, assim como a troca aberta de conhecimento, promovem inovações, tanto de grande como de pequeno porte, e sua divulgação na região.</p>

Table SI IV-7: Selected factors, direction of their effects, and the respective Nagelkerke  $R^2$  of the land use suitability model, received from a logistic regression analysis. We calculated the model based on a stratified random sample of 500 points each (150 points each for urban/settlement) with a minimum distance of 900m referring to 10 pixels

Pasture	Croplands	Urban/Settlements
Distance to capitals (+)	Distance to capitals (-)	Distance to capitals (-)
Distance to roads (-)	Precipitation (-)	Distance to roads (-)
Distance paved roads (+)	Cropland aptitude (+)	Distance to paved roads (-)
Distance to unpaved roads (-)		Distance to unpaved roads (+)
Slope (-)		Slope (-)
Distance to cities (-)		
Distance to rivers (-)		
Nagelkerke $R^2$ 0.35	Nagelkerke $R^2$ 0.78	Nagelkerke $R^2$ 0.79

Chapter V:  
**Synthesis**

## 1 Summary

The overall aim of this dissertation was to contribute to a better understanding of the spatial and temporal dynamics of land use changes and land use displacement dynamics in the Brazilian Amazon under changing environmental governance. The research investigated one of the most active deforestation and commodity expansion frontier in the Brazilian Amazon: the federal states of Mato Grosso and Pará. A focal region of the analysis was the BR-163 highway. Built in 1973, it connects the large-scale agricultural production areas in Mato Grosso with the Amazon harbor in Santarém, Pará, crossing vast tracts of pristine tropical forests. Earlier research indicated that deforestation dynamics within the region were linked to land use displacement processes occurring via the interaction of soybean and cattle ranching activities. Additionally, policies, such as the strategies framed within the action plan to prevent and control deforestation in the Legal Amazon (PPCDAm), and the Soy Moratorium, affected the regional land use dynamics. The core research chapters (Chapter II, III, IV) of this thesis contributed to increasing the understanding of the land use and land use displacement dynamics, at regional and property scale, and for modeling scenarios of land use change.

In the following, the findings of the core research chapters (Chapter II, III, IV) are summarized in respect to the two overarching research question stated in Chapter I:

*Research Question 1: How did land use and land use displacement dynamics change in relation to the PPCDAm and the Soy Moratorium?*

Chapter II and III aimed to evaluate land use and land use displacement dynamics in Mato Grosso and Pará state. Both chapters focused on different spatial scales and policies. Chapter II analyzed regional scale processes using municipality data on deforestation and changes in agricultural production considering the period 2001 to 2012. The analysis focused on changes in land use and displacement dynamics associated with the implementation of the PPCDAm, in Mato Grosso, and along the BR-163 highway. Chapter III provided a property level analysis for the Amazon region of Mato Grosso, analyzing direct and indirect deforestation associated with soybean expansion between 2004 and 2014. The focus of the

analysis was on the contribution of indirect deforestation caused by the expansion for soybeans under the Soy Moratorium commitment.

In Chapter II the deforestation transfer ratio suggested by Gaspari et al. (2013) was applied to characterize the linkages between cattle ranching, soy expansion and deforestation along the BR-163 highway. The results indicated that forest clearings along the BR-163 corridor before the implementation of the PPCDAm in 2004 were linked to an increasing cattle herd. Between 2005 and 2007 deforestation and the expansion of the cattle herd decreased. However, more forest areas per change of cattle numbers were cleared, suggesting excess deforestation stimulated by land speculation. The relatively low deforestation transfer ratio between 2008 and 2011, may on the one hand, suggest that cattle ranching activities have been intensified, following the increased restrictions upon land as a result of the PPCDAm. On the other hand, excessive areas cleared between 2005 and 2007 were likely put under pasture use before deforesting new areas for the growing cattle herd. This would render the decline of the deforestation transfer ratio a temporary effect, and deforestation might increase again once all areas deforested between 2005 and 2007 are used for cattle ranching. Additionally, a panel regression approach provided insights into distal linkages between soybean expansion and deforestation. Two models, one before and one after the implementation of the PPCDAm, were fitted to delineate changes of displacement dynamics related to the policy implementation. The results provide evidence for distal linkages between the expanding areas of soybean production and deforestation for cattle ranching along the BR-163 highway. Soybean expansion in Mato Grosso was significantly correlated to deforestation for cattle ranching along the BR-163 for the 2001-2004 period. This finding corroborated earlier hypotheses of soybean expansion displacing cattle ranching to the deforestation frontier (Arima et al., 2011; Richards, 2012b). However, following the implementation of the PPCDAm increasing rates of soybean expansion in Mato Grosso were no longer reflected in increasing rates of deforestation. The panel regression estimates for 2008-2012 indicated a negative association between the expansion of soybean and deforestation rates along the BR-163. Hence, the analysis suggested a decoupling of soybean expansion in Mato Grosso and deforestation dynamics along the BR-163 highway.

Chapter III provided a property scale analysis, investigating soybean expansion associated with direct and indirect deforestation in the Amazon region of Mato Grosso between 2004 and 2014. Indirect deforestation, not considered within the Soy Moratorium commitment might undermine its effectiveness in reducing overall deforestation. Ten years of land use

and land cover information were intersected with rural cadastre data to map on property land use changes. The methods combined land use accounting and rule-based analysis, to identify and quantify direct and indirect deforestation associated with soybean expansion. Indirect deforestation was defined as on-property displacement and property spillover deforestation. On-property displacement occurred, when soybean expanded over pastures, while simultaneously within the same property, deforestation for cattle ranching occurred. Property spillover described displacement processes occurring across neighboring properties. This process may happen when multiple properties are owned or rented by the same farmer.

The findings indicated that rates of direct deforestation for soybeans declined following the implementation of the Soy Moratorium in 2006. Likewise, indirect deforestation dropped, though at considerable smaller magnitudes. While direct deforestation for cropland continued to decrease throughout the period of analysis, overall deforestation, accounting for direct and indirect deforestation increased during the most recent observation period (2012-2014). The increasing on-property displacement deforestation coincided with increasing global prices for soybeans. This may suggest that indirect deforestation has become a strategy to expand the areas of soybean production without violating the Soy Moratorium.

Overall, land use and land use displacement dynamics changed in response to the implementation of the selected policies. While the results of Chapter II supported the hypothesis of soybean expansion displacing cattle ranching to the forest frontier, thereby contributing to deforestation, these dynamics declined after the implementation of the PPCDAm. Increasing soybean expansion in Mato Grosso was reflected by decreasing deforestation rates along the BR-163, suggesting a temporal decoupling of the distal linkages. Similarly, direct and indirect deforestation for soybean cultivation at property level declined after the implementation of the Soy Moratorium. However, increasing indirect deforestation at property scale, coinciding with increasing prices for soybeans, indicated the risk of future increases of indirect deforestation for soybean production. This would undermine the effectiveness of the Soy Moratorium to ban deforestation from its supply chain.



*Research Question 2: How do scenarios of land use deviate between a cross-scale model-coupling approach and a subregional scenario quantification?*

Chapter IV aimed to evaluate scale effects of regional land use dynamics relevant for land use modeling. Scenario analysis was employed within a coupled land use modeling setup and for a subregional modeling approach. The coupled model setup combined a regional scale land use model with a subregional land use model. The selected subregion referred to a corridor along the BR-163 highway, while the regional scale comprised the area of Mato Grosso and Pará. A trend scenario and a sustainable developments scenario of possible future land uses along the BR-163 corridor, describing the period between 2010 and 2030, were modeled, compared and discussed. The model-coupling employed two land use and land cover maps, each selected for the specific scale of analysis. For the subregional analysis, a new land use model (alucR) was developed as a flexible tool for scenario modeling. The model coupling followed a top-down approach, in which changes of land use derived from the regional scale model (Mato Grosso and Pará) were passed to the subregional scale (BR-163 corridor). This approach preserved the advantages of using scale specific land use information and maintained the consistency between the dynamics of land use changes among the regional and subregional scale.

The results revealed substantial differences of future land use changes along the BR-163 corridor, between the coupled modeling approach and the subregional scenario quantification approach. The two trend scenarios, one referring to the coupled modeling, the other to the subregional quantification, highlighted the BR-163 region as most likely to experience further pasture expansion. This corroborated earlier findings of Lapola et al. (2010a) on land use displacement, indicating the region along the BR-163 as one of the regions of pasture displacement. Cropland expansion occurred mostly outside the BR-163 region throughout all scenarios. In fact, the coupled trend scenario suggested a decrease in cropland along the BR-163 highway. In contrast, the subregional trend scenario projected increases in croplands by 5% until 2030. The overall deforestation differed considerably between the modeling approaches. The subregional trend scenario projected substantially higher forest loss until 2030 than the coupled trend scenario. On the one hand, the regional scale model might underestimate the specific land use and deforestation dynamics associated with the BR-163 corridor. The cropland expansion dynamics indicated in Chapter III were not captured within the regional scale model. On the other hand, the limited extent and the

assumed continuation of past trends within the subregional modeling approach might have led to over-predicting land use changes. Past land use displacements dynamics (Chapter II), might have overly determined the subregional scenario dynamics of land use changes. These differences, between the coupled, and subregional model quantification, stressed the importance of scale for scenario modeling and indicated the need for feedbacks between subregional and regional dynamics. Even though large uncertainties exist, all scenarios highlighted the significance of cattle ranching dynamics as crucial to reduce deforestation along the BR-163 corridor.

## **2 Main conclusions and implications**

The three core research chapters of this thesis (Chapter II, III, IV) contributed to the understanding of land use and land use displacement dynamics affecting deforestation in the Brazilian Amazon. They provided new insights into trends and linkages between soybean expansion in Mato Grosso, cattle ranching and deforestation along the BR-163 between 2001 and 2012 before and after the implementation of the PPCDAm (Chapter II). Moreover, the thesis contributed to the understanding of direct and indirect deforestation for soybean expansion at property scale in the Amazon region of Mato Grosso. It provided the first quantification of indirect deforestation at property level, yet overlooked within the supply chain commitment to ban deforestation from soybean production (Chapter III). Furthermore, insights on land use dynamics across scales and future scenarios of land use change along the BR-163 were obtained. (Chapter IV).

These results relate to three main conclusions and implications of this thesis:

*Deforestation for cattle ranching continues to be driven by land speculation, even though economic profits of cattle ranching increased.*

Excessive deforestation along the BR-163 during the years 2005 to 2007 indicated that deforestation was partly unrelated to changes in cattle herd size. Even though deforestation rates declined during those years, the forest areas cleared were neither equivalent to the past area demands for cattle, nor soybean production. This observation is in line with other studies, which explained deforestation with land speculation, i.e. the clearing of forests to claim lands, rather than the actual needs for pastures (Hecht, 1985; Arima et al., 2005; Richards et al., 2014). In consequence, monitoring and enforcement of environmental

regulations continue to be crucial to combat illegal deforestation in a region partly characterized by a “climate of lawlessness and impunity” (Fearnside, 2007). Particularly promising is the institutionalization of the rural cadastre (Cadastro Ambiental Rural - CAR) as an instrument of land regulation. Compulsory property registration under the legislation of the Forest Code (Código Florestal, 2012) by the end of 2017 will increase the capabilities of the Brazilian environmental agency (IBAMA) to effectively prosecute and punish illegal deforestation (L’Roe et al., 2016). Before the implementation of the CAR, the punishment of illegal deforestation was often inhibited by unknown or obscure land ownerships (Nepstad et al., 2014). Most fines issued for illegal deforestation between 2004 and 2011, accounting for BRL 7.2 billion have never been paid (Nepstad et al., 2014). Moreover, the CAR will bring certainty for landowners on land titles, and hence incentives compliance with the environmental regulations.

*The interaction between cattle ranching and soybean production caused direct and indirect deforestation in the Brazilian Amazon.*

Evidence for distant linkages of soybean expansion in Mato Grosso, driving deforestation for cattle ranching along the BR-163 highway was provided in Chapter II. Furthermore, Chapter III indicated on property displacement processes related to soybean expansion over pastures causing deforestation for cattle ranching in the Amazon region of Mato Grosso. These results suggest that environmental policies in Brazil must recognize and address the interactions between soybean and cattle production contributing to deforestation.

Distal displacements of land use, as indicated in Chapter II are challenging to address within a policy framework. Further advances in the understanding of the causal mechanisms will be crucial to address the underlying processes (Richards, 2012a; Meyfroidt, 2016). However, for the selected study region along the BR-163 highway, this thesis indicated an association between the implementation of the PPCDAm and decreasing deforestation rates, hence contributing to a decoupling between soybean expansion and deforestation along the BR-163 highway. This suggests that land use zoning and monitoring, as well as the enforcement of environmental laws and credit policies, framed within the PPCDAm, were effective in reducing deforestation in the target regions of displacement.

Displacement deforestation assessed in Chapter III occurred in spatial proximity, within one property or among one property and its neighbors. Supply chain governance, as initiated

within the Soy Moratorium and the Cattle Agreements can take a key role in deforestation governance at property level. Integrating efforts between the supply chain actors and the governmental policies aiming to control deforestation seems most promising to decrease deforestation for commodity production. The Soy Moratorium has proven potentials to effectively decrease deforestation for commodity production. Hence, linking between the supply chain actors and IBAMAs efforts to decrease deforestation and enforce the compliance with environmental regulations is understood to be crucial to decrease deforestation.

Moreover, the adoption of alternative farming practices may help to decrease deforestation and other environmental impacts of current agricultural practices in the Amazon. Earlier research has demonstrated that investments in capacity building and technical assistance is crucial to advance the adoption more sustainable land use practices (Gil et al., 2015; Gil et al., 2016; Carauta et al., 2017). Integrated crop-livestock-forestry systems have been identified as a promising pathway of sustainable intensification, increasing organic matter content in the soils and allowing for higher livestock stocking rates in pasturelands (Gil et al., 2015). This can contribute to reconciling trade-off between agricultural production and forest conservation. However, intensification and increased profitability of land use practices come at the risk of bringing more land into production and hence lead to increasing deforestation (Angelsen and Kaimowitz, 2001; Kaimowitz and Angelsen, 2008; Lambin and Meyfroidt, 2011). Balancing trade-offs between economic incentives of land use expansion and environmental protection, e.g. land regulation and land use zoning, will be crucial to prevent deforestation.

*Future land use changes along the BR-163 will be driven by land use displacement and regional dynamics of land use changes*

The comparison of the scenarios derived from the coupled modeling approach and the subregional model demonstrated the importance of regional and local land use dynamics along the BR-163 highway. The dominance of cattle ranching along the BR-163 corroborating findings of Lapola et al. (2010a) who indicated the region as one of the locations affected by pasture displacement. However, high deforestation rates derived from the subregional model stressed the local specific dynamics. In respect of land use modeling, this finding highlighted the importance of scale and related uncertainties for model quantification. In respect of policy implication, this stressed the need to account for region-

specific policies, which account for the regional land use dynamics. Despite the large differences between the scenarios, all scenarios emphasized pasture dynamics as the dominant force for land conversions. Hence, supporting and expanding the current efforts of supply chain governance among the cattle ranching sector (MPF-TAC and G4-Agreement) will be crucial to target deforestation in the Amazon. Essential improvements need to be made in the ability to track and monitor cattle, which is often moved between different properties (Nepstad et al., 2014; Gibbs et al., 2016; Gaworecki, 2017).

### **3 Outlook**

Overall, this dissertation advanced the understanding of the dynamics and interactions between soybean production and cattle ranching in Brazil, causing direct and indirect deforestation in the Amazon. Land use displacement processes associated with soybean expansion are fundamental to complement the understanding of deforestation in the Amazon. Relating these processes to environmental policies contributed to the understanding of their effectiveness and indicated strategies to complement current efforts on environmental governance. This may support strategies to achieve the National Climate Change Policy target, to reduce deforestation by 80% by 2020, compared to its ten-year baseline referring to 1996-2005.

All results gained within this thesis were based on publicly available datasets, most of them available for the Brazilian Amazon or for all of Brazil. Hence, the analyses within this thesis hold the potential to be applied to other regions, or across the whole Brazilian Amazon.

During the course of this thesis, several subjects for possible follow-up research emerged that were beyond the scope of this work.

Increasing the understanding of displacement effects of soybean expansion in Mato Grosso driving deforestation for cattle ranching in the Amazon was also in the interest of other studies. Richards (2015), for example, applied a questionnaire to investigate land use displacement processes along the BR-163 highway. The obtained knowledge increased the understanding of the processes of land use displacement. Following the interviews, he argued that the greater impact of the expanding agricultural sector lies in its effect on land markets in the Amazon. Agricultural expansion attracted new investments, which contributed to increasing the value of land. The rise in land prices was not limited to the soybean expansion areas but also affected land use decision at the forest frontier, increasing incentives to clear

new lands for speculative gains (Richards et al., 2014; Richards, 2015). This analysis contributes to the results in Chapter II, improving the understanding of the mechanisms behind the observed process and increases the awareness of land speculation as an important cause of illegal deforestation. Moreover, distal displacement processes have not only been associated with soybean expansion in Mato Grosso but have also been attributed to sugarcane expansion in south-eastern Brazil (Andrade de Sá et al., 2013; Jusys, 2017). Future research on land use displacement process in Brazil will profit from joining the two discussions. This will allow to increase the understanding of processes causing displacement and to investigate linkages between the sugar cane and soybean expansion on deforestation in the Brazilian Amazon.

Land use and land cover maps provided by TerraClass (INPE, 2015) and gross-deforestation maps provided by PRODES (INPE, 2018) supplied important spatial data on which the analyses of thesis were based. In this context, future improvements in remote sensing products might enhance the possibilities of land use change analysis. In particular, more thematic depth in land use information, for examples, distinguishing crop types and crop rotations, will allow attributing land use changes to the expansion of specific crops and land management systems. A distinction between different crop types within TerraClass, for example, would have decreased uncertainties of the analysis provided in Chapter III regarding the question, if observed changes are caused by soybeans or another crop type.

Additionally, more frequent and comparable land use information will increase the potential for policy relevant land use analyses. In the context of the Soy Moratorium, for example, more frequent land use maps would have enabled the analysis to clearly split between pre- and post-Soy Moratorium land use changes. Future research should assess the effectiveness of the Soy Moratorium for reducing deforestation, compared deforestation among properties cultivating soybeans and properties dedicated to cattle ranching only. To date, no such rigorous comparison exists.

The `alucR` (allocation of land use change in R) land use model for scenario analysis, developed, implemented and applied in Chapter IV, offers large potential to explore different modeling aspects. The model, implemented in the R statistical programming language is currently freely accessible and hosted at Github (Gollnow, 2015). The implementation in R (R Core Team, 2013) allows flexibility for statistical methods of land use suitability estimation (for example, boosted regression trees or neural networks), and adaptation for case study specific assumptions, relevant for the spatial allocation of land uses. Current

efforts aim to integrate spatial explicit processes of land use intensification, including, for example, data on yield gaps into the model. This will expand land use scenario analysis from simple land use conversion to include spatial explicit land use modifications.

Strengthening of open source solutions and accessibility of code in land use modeling may help to increase the participation of researchers to improve current modeling approaches. Together with future increases in fine scale, accurate land use data for large regions this opens new potentials to explore concepts and data integration for implementing feedbacks loops between land use models across scales, to overcome current challenges in land use modeling (Brown et al., 2014; Verburg et al., 2015).

In summary, this thesis provided new insight into the interactions between cattle ranching and soybean expansion causing direct and indirect deforestation in the federal states of Mato Grosso and Pará, Brazil. Deforestation along the BR-163 highway was affected by land use displacement dynamics driven by the large-scale expansion of soybean production. Following the implementation of environmental policies, these displacement dynamics declined. However, increasing rates of deforestation question the persistence of the observed decoupling between deforestation and soybean expansion. At property level indirect deforestation for soybean expansion increased during the most recent observation period, undermining the effectiveness of the Soy Moratorium. Future scenarios of land use change indicated that land use dynamics along the BR-163 highway will be driven by local and regional dynamics of land use change. Based on these findings policies targeting deforestation need to acknowledge the interactions between soybean and cattle production contributing to deforestation in the Amazon. Integrating actions between actors, the soybean and beef industries and IBAMAs efforts to decrease deforestation, in combination with capacity building and technical assistance to support farmers in adapting alternative agricultural practice will be crucial to steer agricultural development and reduce deforestation of a globally valuable forest ecosystem.





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## Publikationen

### PEER-REVIEWED JOURNAL ARTICLES

#### *Published manuscripts*

- [3] **Gollnow, F.**, Göpel, J., Hissa, L.B.V., Schaldach, R., Lakes, T. (2017): Scenarios of land-use change in a deforestation corridor in the Brazilian Amazon: combining two scales of analysis, *Regional Environmental Change*.
- [2] Pinheiro, T.F., Escada, M.I.S., Valeriano D.M., Hostert, P., **Gollnow, F.**, Müller, H. (2016): Forest degradation associated with logging frontier expansion in the Amazon: the BR-163 region in southwestern Pará, Brazil, *Earth Interactions*, 20 (17), 1-26.
- [1] **Gollnow, F.**, Lakes, T. (2014): Policy Change, Land Use, and Agriculture: The case of soy production and cattle ranching in Brazil, 2001-2012, *Applied Geography*, 44, 203-211.

#### *Submitted manuscripts (submitted or in review)*

- [4] **Gollnow, F.**, Hissa, L.B.V., Rufin, P., Lakes, T. (submitted): On property deforestation for soybean production in Mato Grosso, Brazil: investigating direct deforestation, on-property displacement, and property spillover deforestation, *Land Use Policy*.
- [3] Schägner, P., Maes, J. **Gollnow, F.**, Bertzky, B., Brander, L., Parracchini, M.L. (submitted): Spatial Dimensions of Recreational Ecosystem Service Values: A Review of Meta-Analyses and a Combination of Meta-Analytic Value-Transfer and GIS, *Ecosystem Services*.
- [2] Schaldach, R., Meurer, K.H.E., Jungkunst, H.F. Nendel, C., Hampf, A., Parker, P.S., Sentelhas, P.C., Lakes, T., **Gollnow, F.**, Göpel, J., Boy, J., Guggenberger, G., Strey, R., Strey, S., Latynskiy, E., Berger, T., Schindelwolf, M. Schönenberg, R., Böhner, J. Gerold, G. (in review): A model-based assessment of land-use change and its environmental impacts on multiple scales in Southern Amazonia, *Regional Environmental Change*.
- [1] Schoenenberg, R., Goepel, J., Schaldach, R., **Gollnow, F.**, Lakes, T. (in review): Inter- and transdisciplinary scenario construction to explore future land use options in Southern Amazonia. *Ecology and Society*.

### CONFERENCE CONTRIBUTIONS

#### *Conference presentations*

- [6] **Gollnow, F.**, Göpel, J., Lakes, T., Schaldach, R. (2015): A Multi-Scale Land Use Modeling approach for the Brazilian Amazon, IALE World Congress, Portland, United States of America.

- [5] Lakes, T., **Gollnow, F.**, Göpel, J., Schaldach, R. (2015): Future development paths of local land use changes within a globally changing world – a Multi-Scale Land Use Modeling approach for the Brazilian Amazon, Deutscher Kongress für Geographie (DKG), Berlin, Germany.
- [4] Oeser, J., Santibanez, S., **Gollnow, F.**, Lakes, T., Kloft, M. (2015): Maschinelles Lernen zur Modellierung raum-zeitlicher Prozesse, Deutscher Kongress für Geographie (DKG), Berlin, Germany.
- [3] **Gollnow, F.**, Lakes, T. (2014): De-spatialization of land use change? Soy expansion and cattle displacement in the Brazilian Amazon, GLP Open Science Meeting 2014, Berlin, Germany.
- [2] **Gollnow, F.**, Estreguil, C., Dubois, G., Mayaux, P., Caudullo, G. (2010): Fragmentation and connectivity analyses of African forested protected areas, ForestSat 2010, Lugo, Spain.
- [1] van der Linden, S., Waske, B., Rabe, A., **Gollnow, F.**, Griffiths, P., Kümmerle, T., Hostert, P. (2009): On the use of support vector machines and decision trees in land cover mapping - a review from the user perspective, 3rd Workshop EARSeL SIG Land Use and Land Cover, Bonn, Germany.

Conference posters

- [3] **Gollnow, F.**, Mönkemeier, T., Lakes, T. (2016): An Open and Flexible Land Use Model for Scenario Assessments alucR (Allocation of Land Use/Cover in R), AGILE Conference, Helsinki, Finland.
- [2] **Gollnow, F.**, Lakes, T. (2015): Policy changes as a breakpoint in land use displacement in the Brazilian Amazon? Evidences for changes in deforestation, soy production and cattle ranching between 2001 and 2012 case study along the BR-163, IALE World Congress, Portland, United States of America.
- [1] **Gollnow, F.**, Lakes, T. (2013): Statistical evidence for indirect land use change at the "arc of deforestation" Brazil, case study along the BR-163 (Mato Grosso & Pará), Spatial Statistics Conference, Ohio, United States of America.

Conference session chairs

**Gollnow, F.**, Schaldach, R. (2015): Szenarien der Landnutzung - multiskalige Modellierungsansätze in einer globalisierten Welt, Deutscher Kongress der Geographie (DKG), Berlin, Germany.







## **Eidesstattliche Erklärung**

Hiermit erkläre ich, die vorliegende Dissertation selbstständig und ohne Verwendung unerlaubter Hilfe angefertigt zu haben. Die aus fremden Quellen direkt oder indirekt übernommenen Inhalte sind als solche kenntlich gemacht. Die Dissertation wird erstmalig und nur an der Humboldt-Universität zu Berlin eingereicht. Weiterhin erkläre ich, nicht bereits einen Dokortitel im Fach Geographie zu besitzen. Die dem Verfahren zu Grunde liegende Promotionsordnung ist mir bekannt.

Florian Gollnow

Berlin, den 06.06.2017