A scenario approach to modeling land-use changes and assessing associated environmental impacts in Southern Amazonia

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Abstract

Humanity has left its footprint on the surface of the earth since it managed to purposefully employ tools and fire to its specific needs. Especially the conversion of natural habitats into agricultural productive land has transformed close to forty percent of the natural land-cover in order to satisfy global demands for food, raw materials, and energy. One current example of dynamic land-use and land-cover changes can be witnessed in Southern Amazonia. Spatially explicit land-use change models are applied to investigate such processes and to identify associated environmental impacts in a multitude of cases. In this context, land-use change models are utilized to understand the determining factors of past and current land-use change dynamics. This knowledge can be put to use in order to explore possible future land-use development pathways. However, modeled land-use and land-cover changes show sensitivities to used model input and applied methods. Modeling these dynamics based on different land-cover products, input sources and methods to estimate parameter weights on a regional scale can result in a range of modeling and subsequent impact assessment results. Therefore, the first objective of this thesis is to explore sensitivities of land-use change modeling- and subsequent impact assessment results to different initial land cover products, input variables derived from different sources, and different methods used for model parameter estimation. Modeling possible future land-use change requires assumptions about the development of its determining factors. Socio-economic scenarios include speculations about population development, changes of global demand and supply, and political changes amongst others. Based on this information, possible future land-use trajectories can be explored and associated environmental consequences can be assessed. The second research objective is to investigate possible future land-use change by assuming four different scenarios. The resulting spatially explicit land-use change allows for an investigation of impacts in the form of greenhouse gas emissions. Moreover, in this thesis the ensuing loss of natural vegetation and vertebrate diversity are assessed. Modeling land-use and land-cover change on the basis of combined qualitative and quantitative scenarios has advantages. However, one challenge of generating such scenarios is the translation of qualitative assumptions into numerical model input that can be used to simulate land-use change scenarios. Consequently, the third research objective is to critically review and analyze the process of translating qualitative assumptions into suitable model inputs in regard to the scenarios applied in this thesis. The findings of this thesis can aid future land-use and land-cover change modeling exercises and can be used to improve future scenario development processes. Moreover, the regional modeling of land-use and land-cover changes and the assessment of associated environmental impacts on the basis of assumed socio-economic developments gives a detailed impression of how the land-use future might unfold in Southern Amazonia. Also, the results can be utilized to research possible land-use policy implications in the study area.

Zusammenfassung

Seitdem es die Menschheit vermag Werkzeuge und Feuer für ihre speziellen Bedürfnisse einzusetzen, hat sie ihren Fußabdruck auf der Oberfläche der Erde hinterlassen. Vor allem die Umwandlung von natürlichen Lebensräumen in landwirtschaftliche Nutzflächen hat nahezu 40 Prozent der natürlichen Landbedeckung beeinflusst, um die globale Nachfrage nach Nahrung, Rohstoffen und Energie zu erfüllen. Ein aktuelles Beispiel für dynamische Landnutzungs- und Landbedeckungs-Veränderungen kann in Süd-Amazonien beobachtet werden. Räumlich explizite Landnutzungsmodelle werden in einer Vielzahl von Fällen angewendet, um diese Prozesse zu untersuchen und die damit verbundenen Umweltauswirkungen zu identifizieren. In diesem Zusammenhang werden Landnutzungsmodelle verwendet, um die bestimmenden Faktoren der vergangenen und gegenwärtigen Landnutzungsänderungsdynamik zu verstehen. Dieses Wissen kann genutzt werden, um mögliche zukünftige Entwicklungstrajektorien zu erforschen. Allerdings zeigen modellierte Landnutzungs- und Landbedeckungs-Änderungen Sensitivitäten in Bezug auf Modelleingabewerte und angewandte Methoden. Die Modellierung dieser Dynamiken auf der Grundlage unterschiedlicher Landbedeckungsprodukte, Input-Quellen und Methoden zur Schätzung von Parametergewichten auf regionaler Ebene kann zu einer Spannbreite von Modellierungs- und nachfolgenden Folgenabschätzungsergebnissen führen. Daher ist es das erste Ziel dieser Thesis, Sensitivitäten der Landnutzungsänderungsmodellierung und der Ergebnisse der nachfolgenden Folgenabschätzung auf unterschiedliche anfängliche Landdeckungsprodukte, aus verschiedenen Quellen abgeleitete Eingangsvariablen und verschiedene Methoden, die für die Modellparameterschätzung verwendet werden, zu erforschen. Die Modellierung möglicher zukünftiger Landnutzungsänderungen erfordert Annahmen über die Entwicklung ihrer bestimmenden Faktoren. Zu sozioökonomischen Szenarien gehören, unter anderem, Spekulationen über die Bevölkerungsentwicklung, Veränderungen der globalen Nachfrage und des Angebots sowie politische Veränderungen. Auf der Grundlage dieser Informationen können mögliche zukünftige Landnutzungsentwicklungen erforscht und damit verbundene Umweltauswirkungen beurteilt werden. Das zweite Forschungsziel besteht darin, basierend auf vier verschiedenen sozioökonomischen Szenarien, mögliche zukünftige Landnutzungsänderungen zu untersuchen. Die daraus resultierenden räumlich expliziten Landnutzungsänderungen ermöglichen eine Untersuchung von Umweltauswirkungen in Form von Treibhausgasemissionen. Darüber hinaus wird in dieser Thesis der resultierende Verlust an natürlicher Vegetation und der dort beheimateten Wirbeltier-Diversität beurteilt. Die Modellierung von Landnutzungs- und Landbedeckungs-Veränderungen auf der Basis von kombinierten qualitativen und quantitativen Szenarien hat Vorteile. Allerdings liegt hierbei eine Herausforderung in der Übersetzung von qualitativen Annahmen in numerische Modelleingabegrößen, die zur Simulation von Landnutzungs-Szenarien verwendet werden können. Das dritte Forschungsziel besteht daher darin, den Prozess der Übersetzung qualitativer Annahmen in geeignete Modelleingabegrößen in Bezug auf die in dieser Arbeit angewandten Szenarien kritisch zu überprüfen und zu analysieren. Die Ergebnisse dieser Thesis können künftige Modellierungen von Landnutzungs- und Landbedeckungsänderungen unterstützen und weitergehend genutzt werden, um zukünftige Szenario-Entwicklungsprozesse zu verbessern. Darüber hinaus gibt die regionale Modellierung von Landnutzungs- und Landdeckungsänderungen und die Bewertung der damit verbundenen Umweltauswirkungen auf der Grundlage der angenommenen sozioökonomischen Entwicklungen einen detaillierten

Eindruck, wie sich eine mögliche Landnutzungs-Zukunft in Süd-Amazonien entfalten könnte. Auch können die Ergebnisse genutzt werden, um mögliche Auswirkungen einer sich verändernden Landnutzungspolitik im Studiengebiet zu beurteilen.

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List of Acronyms

AHP	Analytical hierarchy process
BAU	Business-as-usual scenario
BGB	Below ground biomass
BII	Biodiversity Intactness Index
CarBioCial	Carbon sequestration, biodiversity, and social structures in Southern Amazonia
CESB	Centro Brasileiro das Empresas Simuladas
CRITIC	Criteria importance through intercriteria correlation
EMBRAPA	Empresa Brasileira de Pesquisa Agropecuária
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross domestic product
GHG	Greenhouse gas
GLC2000	Global land-cover 2000
IBGE	Instituto Brasiliero de Geografia e Estatística
IBGP	International Geosphere Biosphere Program
INPE	Instituto Nacional de Pesquisas Espaciais
IPCC	Intergovernmental Panel on Climate Change
IPEA	Instituto de Pesquisa Econômica Aplicada
IUSS	International Union of Soil Sciences
LandSHIFT	Land Simulation to Harmonize and Integrate Freshwater Availability and the Terrestrial Environment
LCCS	Land Cover Classification System
LPJmL	Lund-Potsdam-Jena managed Land
LULCC	Land-use and land-cover change
MCA	Multi criteria analysis
ME	Model efficiency
MMA	Ministerio do Meio Ambiente
MODIS	Moderate Resolution Imaging Spectroradiometer
MONICA	Model of Nitrogen and Carbon dynamics in Agro-ecosystems
MT	Mato Grosso
OECD	Organization for Economic Cooperation and Development
PA	Pará
PPCDAM	Plan to prevent and control deforestation

PRODES	Projecto de Monitoramento do Desmatamento na Amazônia Legal por Satélite
SOC	Soil organic carbon
SRTM	Shuttle Radar Topography Mission
STAR	Statistical Regional Model
UNEP	United Nations Environment Program

Chapter 1: Introduction

1. Introduction

1.1. Background

Humanity has left its footprint on the surface of the earth since it managed to purposefully employ tools and fire to its specific needs. Approximately 10.000 years ago, with the domestication of animals and plants, the human alteration of the landscape (further referred to as land-use and land-cover changes: LULCC) due to sedentary agriculture began to exceed the land-cover changes caused by the natural occurrence of fire (Ramankutty et al. 2006). These dynamics have considerably increased in speed and extent over the last 300 years due to the utilization of fossil fuels as a means of energy provision, the application of new agricultural technologies as well as the industrial production of fertilizers (Ramankutty and Foley 1999). Today, anthropogenic activities to systematically change the terrestrial surface of the planet have converted 38.5% (FAOSTAT 2013) of the earth´s land-cover into agricultural land in order to provide food for a growing population. In 2014, close to 16 million square kilometers of terrestrial earth surface have been converted into cropland and more than 33 million square kilometers have been converted into permanent meadows and pastures (FAOSTAT 2013).

On the one hand, expansion of cultivated areas and the intensified management of existing farmland have helped to secure and increase the amount and quality of food provision for a growing world population. Moreover, agricultural expansion and intensification allow for economic growth and increasing prosperity in regions that are suitable for agricultural production (World Bank Group 2016). On the other hand, agricultural expansion and intensification have reduced and will reduce the extent of natural ecosystems and quantitatively as well as qualitatively diminish the provision of essential services such as: production of food and water, climate regulation, support of biological processes (e.g. pollination), and recreational benefits. To name just a few examples; agricultural expansion causes loss and fragmentation of ecosystems, species extinction and thus, loss of biodiversity (Millennium Project 2008a; Newbold et al. 2015; Chaplin-Kramer et al. 2015). Water quality can decrease due to nitrogen leaching from intensively fertilized cropland as a consequence of agricultural intensification (Seitzinger et al. 2010; Fink et al. 2017). Waterways are straightened to increase the availability of freshwater in intensively cultivated areas, also increasing the damage done by flooding events (Millenium Ecosystem Assessment 2005; Laitinen 2008). Soils can degrade due to livestock overgrazing, agricultural mismanagement or slash and burn methods, causing an increased risk of soil erosion and a reduction of soil fertility (Capistrano 2005; Millennium Project 2008b). The atmosphere has experienced and will experience elevated emissions of greenhouse gases (GHG) from agriculture released mainly due to forest conversion and agricultural forest use (Fearnside 2000; Fearnside et al. 2016), land management (e.g. fertilizer application) (Snyder et al. 2009), and the structure of anthropogenic consumption patterns (e.g. livestock for meat production) (O´Mara 2012) contributing to changes of the global climate (Steffen et al. 2015).

In a global perspective, these processes are mainly driven by the constant growth of the human population and the subsequent need for increasing agricultural production as well as changes to the income (per capita GDP) and consequent changes of food consumption (Pingali 2007; Zhai et al. 2014). But especially in a regional perspective, a multitude of other influencing factors have to be taken into account. Here, demographic factors like the distribution and composition of the population, migration, either in or out of particular areas (Moran 2005), the access to technological innovations, property rights, political and economic institutions as well as cultural change play a pivotal role when investigating the location and magnitude of LULCC (Geist and Lambin 2002; Lambin and Geist 2006).

Land-use change models can be applied to investigate past LULCC processes in order to identify relevant drivers of land-use changes, thus contributing greatly to an increased scientific understanding of current and future land-use changes (Lambin et al., 2000; Parker et al., 2003). Moreover, they can be applied to quantitatively and spatially investigate possible future LULCC on the basis of identified drivers. This is done by changing one or more influencing variables (drivers) based on assumptions regarding future socio-economic and biophysical development (Veldkamp and Lambin 2001). Hence, one essential application of LULCC models in combination with scenarios is to test expected or planned changes (e.g. social, economic, political) in regard to their effect on the environment (Verburg et al. 2004).

One kind of scenario, the business-as-usual scenario (BAU), is defined by assuming current conditions to develop according to a trend that can be deduced by observing past developments of population, anthropogenic behavior, policies, economics, and technologies (Alcamo and Ribeiro 2001). This kind of scenario is used as a baseline for scenarios that reflect changes in these trends. Scenarios can be compared to each other, allowing for an evaluation of possible consequences in relation to one another (Alcamo 2008). This can, for example, be relevant in policy analysis as it facilitates an ex ante investigation of possible consequences of new policies as well as in environmental analysis where it enables the examination of environmental consequences based on assumed development trajectories as well as testing of feasible options of, for instance, agricultural development that combine a sustained food provision and a conservation of natural capital (in the form of ecosystems, the services they provide and the diversity they comprise) (Veldkamp and Verburg 2004; Koch 2010).

The development, analysis, and comparison of modeled scenarios (Scenario Analysis) (Alcamo et al. 2008) has been applied to environmental issues in a myriad of cases. A few examples are the Global Environmental Outlook scenarios with their fifth installment (UNEP 2012), the OECD Environmental Outlook up to 2030 (OECD 2008) as well as the Millennium Ecosystem Assessment scenarios with a focus on evaluating the potential development paths for ecosystems and their services up to 2050 (Carpenter et al. 2005). All of the mentioned scenarios have in common that they combine qualitative (description of possible futures in narrative form) and quantitative scenarios (description of possible futures in numerical form). The same can be said about the scenarios applied throughout this thesis. The qualitative scenarios have been developed by integrating stakeholders and experts in the study area within the framework of the Carbiocial project. The translation of the resulting qualitative information into numerical model input has been realized by the author of this thesis in constant consultation with the partners in this project.

1.2. Study Area

Brazil claims to be a “Developmental State” (Woo-Cummings 1999; Hochstetler and Montero 2013), meaning that it tries to shape society and economy according to its visions of a great Brazilian future. This implies that especially regions that bear a strong potential for agricultural development are highly dynamic in terms of LULCC. The spatial focus of this thesis lies on Southern Amazonia or, more specifically, on two Brazilian federal states – Pará (PA) and Mato Grosso (MT). Throughout the last decades, Southern Amazonia was faced with massive LULCC (Coy 2001; Kohlhepp 2002; INPE 2013) that went hand in hand with high deforestation rates (MMA 2001; Morton et al. 2006; INPE 2013). Moreover, MT and PA are diverging regarding their level of agricultural development.

PA has an area of 1.25 million km^2 and a population of 8 million people (IBGE 2015). In 2015 1,881 km^2 were deforested which is about the same amount of deforestation as in 2014 (INPE 2015). PA comprises 147,960 km^2 of cropland and 102,675 km^2 of pastures (IBGE 2013). In contrast to MT, here the potential for agricultural expansion as well as intensification is high (Laurance et al. 2014). A hot spot of LULCC is along the Cuiabá-Santarem highway (BR-163), the most recent of the “development highways” which are used to make accessible the agriculturally rather underdeveloped northern parts of Brazil for crop cultivation and cattle ranching (Coy & Klingler 2008). The natural vegetation is dominated by dense rainforest

(Amazon biome) (Vieira et al. 2008) covering about 77.6% of the state's area according to MODIS land cover data (Friedl et al. 2010). More than 40,000 vascular plant species can be found here, of which 30,000 are endemic (Vieira et al. 2008). Over 1,000 bird species are harbored in the Amazon biome (Vieira et al. 2008) as well as a high concentration of mammals, of which many are endemic, especially along the courses of the rivers crossing this biome (Jenkins et al. 2015). Of the 875 amphibian species in the country, approximately 50% are concentrated in the Amazon biome (Jenkins et al. 2015).

MT has an area of 907,000 km^2 and a population of 3.2 million inhabitants (IBGE 2015). Here 1,508 km^2 were deforested in 2015 which constitutes an increase of 16% in comparison to 2014 (INPE 2015). MT comprises 221,389 km^2 of cropland and 168,198 km^2 of pastures (IBGE 2013). Here the expansion of area used for soybean cultivation and cattle ranching could be identified as the primary cause of conversion of natural ecosystems to agricultural land (Greenpeace-Brazil 2009; Barona et al. 2010). In comparison to PA, MT is more consolidated in terms of agricultural expansion. In recent years, the declining availability of highly productive farmland, policies to curb deforestation and rising land prices have led to a development towards agricultural intensification and away from agricultural expansion (e.g. VanWey et al. 2013; Spera et al. 2014; Cohn et al. 2014). MT is covered by two Brazilian biomes, the Brazilian Cerrado and the Amazon rainforest (e.g. Jenkins et al. 2015; Dias et al. 2016). Here, 7,000 plant species, of which 44% are endemic to the Cerrado, can be found. The Cerrado biome is especially rich in bird diversity with 837 species which correspond to 49% of all bird species found in Brazil. But also 150 reptile species (50% of all Brazilian reptile species) and 180 amphibian species (28 % endemic to the Cerrado) are found here. The Cerrado biome and its waterways are home to 1,400 fish species, 40% of all fish species occurring in Brazil (Klink & Machado, 2005).

1.3. Objectives of this thesis

The overall objective of this thesis was to conduct a model-based analysis of land-use changes and the subsequent analysis of associated environmental impacts in Southern Amazonia. For this purpose the LandSHIFT model (Schaldach et al. 2011) had to be adapted to the biophysical and socio-economic conditions in Southern Amazonia. The adapted regional version of LandSHIFT, which now operates on a spatial resolution of 900x900m, was then evaluated and sensitivities corresponding to the model input and method to estimate parameter weights were assessed. The first research objective is related to the sensitivities of modeling results to the mentioned inputs and methods.

To investigate the reconcilability of an increasing agricultural production in order to fulfill anthropogenic consumption demands and the minimization of negative consequences on ecosystems and biodiversity, a set of four scenarios of agricultural development was constructed and simulated covering a time period of 20 years (2010-2030). Important elements of the stakeholder-generated, narrative scenarios (storylines) were related to land-use policies and agricultural intensification. In order to reflect these assumptions more accurately, LandSHIFT has been further enhanced by integrating a new agricultural land-use type and a new process that describes the further intensification of pasture management. Based on the ensuing simulation of scenarios of LULCC with the enhanced and regionally adapted model version, an assessment of environmental consequences was conducted. The second research objective addresses the modeled land-use scenarios and resulting environmental consequences.

One crucial step of generating combined qualitative and quantitative scenarios is the process of translating storylines into suitable model inputs that can be used to generate quantitative scenarios. The third research objective focusses on this translation process and its effectiveness.

Specifically, the first research objective is: to explore sensitivities of land-use change modeling- and subsequent impact assessment results to (1) different initial land cover products, (2) input variables derived from the most commonly utilized databases (in respect to the study region) and (3) the variety of model parameter values resulting from different methods used for model parameter estimation. Furthermore, a possible range of modeling results that can be attributed to the sensitivities is to be identified.

This objective is realized by the following steps:

- <u>Adaptation of the land-use change modeling framework LandSHIFT:</u> The LandSHIFT model is adapted to reflect the biophysical and socio-economic conditions of the study area. This includes a refinement of its resolution to 900x900m, which facilitates an investigation of land-use processes on the regional scale.
- <u>Assessing land-use change modeling sensitivities and the resulting range of LULCC modeling results:</u> LULCC is simulated based on two different land-cover datasets, two different statistical databases, and the estimation of parameter weights utilizing two different methods. Sensitivities of the model results lead to a range of model results (i.e. spatially explicit LULCC), which is determined and possible sources of the sensitivities are investigated.
- <u>Model evaluation:</u> For each model setup combination, model efficiency (Nash & Sutcliffe 1970; Loague & Green 1991) on the municipality level and the Fuzzy Kappa

coefficient (Hagen-Zanker, 2006) on the grid level are determined. This allows for the identification of the model setup combination that is most suitable to be applied to modeling LULCC in respect to the selected study area and resolution of the land-use change model.

- Investigation of the uncertainties concerning subsequent impact assessment results: Modeled land-use data is used as input for the simulation of GHG-emissions as a consequence of LULCC. Uncertainty in regard to the modeled GHG-emissions is adopted through the sensitivities of land-use change modeling results to the mentioned inputs and methods and can be expressed as a range of GHG-emission modeling results.

The second research objective is: to investigate land-use changes, in terms of location and extent, which can be expected by assuming four different development pathways for Southern Amazonia. Moreover, environmental consequences of the simulated land-use changes in terms of GHG-emissions and the effect of a conversion of natural habitats on the distribution ranges of vertebrate species are to be assessed.

This objective can be divided into following steps:

- Simulation and assessment of land-use changes based on 4 different development pathways: Four socio-economic scenarios comprising qualitative and quantitative information are simulated with the LandSHIFT model. Land-use changes are assessed for each scenario employing GIS software.
- Calculation of N_2O- and CH_4-fluxes from agricultural soils: Average N_2O-and CH_4-emissions reported for different land-use types in Brazil (Meurer et al. 2016) are utilized to calculate N_2O-and CH_4-emissions in regard to each land-use scenario. The assessed land-use types (cropland, pasture) are further distinguished by age (>10 years; ≤10 years).
- Calculation of CO_2-fluxes from agricultural soils: CO_2-release and uptake are derived from changes in soil organic carbon stocks that have been investigated in the course of field experiments (Strey et al. 2016). The CO_2-fluxes resulting from each land-use scenario are considered for two land-use types (cropland, pasture) further distinguished by age (>10 years; ≤10 years) and soil type (Acrisol, Ferralsol).
- Assessment of the effect of a conversion of natural habitats on the distribution ranges of vertebrate species: Modeled land-use maps for each land-use scenario and maps of vertebrate diversity are spatially linked employing GIS software. Thereby areas that

combine natural habitat loss (i.e. LULCC) and the occurrence of vertebrate species can be identified. The Biodiversity Intactness Index (BII) (Scholes & Biggs 2005) based on land-use type, spatial information regarding the number of vertebrate species and a population impact derived from literature is calculated.

The third research objective is: to critically review and analyze the process of translating stakeholder-generated storylines into suitable model inputs that can be used to generate quantitative scenarios.

The following steps are necessary to achieve this objective:

- <u>Description and critical review of the process of translating storylines into suitable model input applied in the CarBioCial project:</u> A crucial step in the development of combined qualitative and quantitative scenarios is to translate stakeholder generated scenarios into numerical model input while maintaining consistency. The translation process that led to the scenarios employed in this study is described and possible sources of inconsistency are investigated.
- <u>Analyze the effectiveness of this process:</u> The effectiveness of the described process is analyzed by identifying the uncertainties that arise in the translation process.

1.4. Structured overview

This thesis consists of six chapters. Following the introduction chapter, the second chapter discusses the first research objective. Chapter three as well as chapter four address the second research objective. Chapter five relates to the third research objective. Chapter two, three, and four have been published or submitted to peer-reviewed journals, and are thus included as self-contained chapters. Consequently each of them has its own introduction, methods & materials, results, and discussion/conclusion section. Therefore, recurrence is unavoidable throughout the different chapters. The following section shortly describes each chapter.

Chapter 1 – Introduction – This chapter provides the theoretical background for the thesis. It gives an overview of why and how land-use simulation models are applied for an analysis of past, current, and future LULCC. Furthermore it is described why scenarios are an essential tool to investigate the effect of possible development trajectories on future land-use, and thus the environment. Moreover, it introduces the reader to the study area. Finally, the research objectives of this thesis are described in detail.

Chapter 2 – Sensitivity assessment and evaluation of a spatially explicit land-use change model for Southern Amazonia – This chapter systematically explores the sensitivity of model results to the use of different inputs and methods. Furthermore, the effect of these sensitivities, expressed as a range of model- and subsequent environmental impact assessment results, is investigated.

Chapter 3 – Scenarios of future land-use and land-cover change in Southern Amazonia and resulting greenhouse gas emissions from agricultural soils – This chapter investigates a set of four land-use scenarios for Southern Amazonia that go beyond assumptions regarding deforestation and include national and international drivers of land-use change (e.g. demands for agricultural commodities and yield increases due to intensification) as well as a detailed representation of regional land-use policies (e.g. *Brazilian Forest Code).* Based on the scenario calculations, resultant greenhouse gas emissions (CO_2, N_2O, and CH_4) from agricultural soils are assessed.

Chapter 4 – Assessing the effects of agricultural intensification on natural habitats and biodiversity in Southern Amazonia – The conversion of natural habitats in respect to four socio-economic scenarios and the distribution ranges of vertebrate species are spatially linked. The investigated vertebrate species are subdivided into three different taxa (mammals, birds, and amphibians) and three categories (threatened species, small-ranged species, endemic species) per taxon. Additionally, the indicator Biodiversity Intactness Index (BII) (Scholes & Biggs 2005) is calculated for PA and MT.

Chapter 5 – The process of translating qualitative scenario assumptions into quantitative model input and associated uncertainties – This Chapter critically reviews the process of quantifying qualitative scenario assumptions in the context of maintaining consistency. This process is described and analyzed in regard to its effectiveness by identifying uncertainties that arise in the translation process. Additionally, ways to improve the translation process are proposed.

Chapter 6 – Synthesis – This chapter summarizes findings of the thesis in light of the encompassing research objectives. Finally, the limitations and advantages of this thesis are discussed and an outlook is presented that identifies possible future research needs as well as possible applications of the findings of this thesis.

Chapter 2: Sensitivity assessment and evaluation of a spatially explicit land-use change model for Southern Amazonia

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Ecological Modelling (in Review)

Abstract

Land-use and land cover change (LULCC), in particular in Amazonia has exerted and will exert crucial influence on global climate and environmental change. Many models were applied to reproduce observed LULCC and explore possible future conversion trends. Results thus far have shown that LULCC modeling, especially in a regional context in Amazonia, needs further research in order to assess the change trajectories that were observed since the end of the 20th century in a complete and cogent way. The lack of modeling results that reproduce observed LULCC dynamics is mostly based upon uncertainties that arise when employing different sets of initial land use data, model input data (drivers), and methods to estimate parameter weights. Also uncertainties in regard to model structure and, thus different representations of modelled processes, have to be taken into account. We therefore chose the well-established dynamic, spatially explicit, integrated LULCC modeling framework, LandSHIFT, to investigate the effect of (1) different initial land-cover products, (2) input variables derived from the most commonly utilized databases and (3) the variety of model parameter weights resulting from different methods used for model parameterization, on modeling results. We then analyzed the resulting model output in order to determine the ability of the model to capture observed LULCC with respect to the chosen combination of input and methods. We measured the predictive performance of the land-use change modeling framework by calculating model efficiency as well as Fuzzy Kappa coefficient. The two Brazilian federal states Mato Grosso and Pará were chosen as focus of this study because they are characterized by highly dynamic LULCC processes as well as large areas of intact natural vegetation that are threatened to be destroyed due to agricultural and pasture expansion. The amount of greenhouse gas (GHG) emissions that is going to be emitted due to deforestation processes was investigated in order to show the range of predictions of environmental impacts that can result from sensitivities in land-use change simulations. Our findings show that a high degree of uncertainty regarding LULCC and estimates of GHG emissions due to LULCC can be expected, depending on the choice of initial land cover product, input variable source, and method used to estimate parameter weights.

1. Introduction

Throughout the last decades, Southern Amazonia was faced with massive land use and land cover changes (INPE, 2013; Kohlhepp, 2002; Coy, 2001). These alterations were conditioned by an accelerated growth of the population combined with an ongoing trend towards urbanization (Coy & Klingler, 2008), accelerated migration due to Brazilian colonization strategies which started in the 1970´s (Almeida & Acevedo, 2010), the lack of land tenure definitions and property rights (e.g. Araujo et al., 2009), and extremely high deforestation rates (MMA, 2001; Morton et al., 2006; INPE, 2013). Deforestation in the study area increased from 18,226 km^2 per year in 2000 to 27,772 km^2 per year in 2004 (INPE, 2013). Main drivers of deforestation included the demand of new land area for crop cultivation or cattle ranching and speculative intentions as well as the steadily increasing international demand for tropical timber (Fearnside, 1987). In the late 2000s this deforestation could be slowed down considerably (Boucher et al., 2013). In 2012, deforestation rates decreased to 4,571 km^2 per year (INPE, 2013; Boucher et al., 2013) which can be explained (1) by initiatives and interventions of the Brazilian government and the local authorities of Mato Grosso (MT) and Pará (PA) (Assunção et al., 2012; Nepstad et al., 2014; Gibbs et al., 2015, 2016) and, (2) by the decrease of world market prices for soybean (Nepstad et al., 2009; Hecht, 2011; Assunção et al., 2012). The most important policies that had a constraining effect on deforestation were the plan to prevent and control deforestation (PPCDAM) which took effect in 2004 (Assunção & Rocha, 2014), the soy moratorium (Gibbs et al., 2015) enacted in 2006 and the cattle agreement from 2009 (Nepstad et al., 2014; Gibbs et al., 2016). But a resurgence of deforestation and cropland/cattle ranch expansion rates can be expected as soon as the Cattle Agreement runs out (Nepstad et al., 2014) and world market prices for soy and cotton increase again. In addition, LULCC has a non-negligible impact on GHG emissions. According to the World Resource Institute the contribution of GHG emissions from LULCC and forestry to the total anthropogenic GHG emissions in Brazil accounts to 45.9% in 2010 (CAIT, 2015). Other studies have found similar values for the contribution of LULCC-induced GHG emissions to Brazil's total carbon balance (e.g. Lapola et al., 2014).

Important tools to gain an improved scientific understanding of current and future land-use changes are simulation models (Lambin et al., 2000; Parker et al., 2003). For the Amazon region a number of different studies exist, employing a wide range of land-use change models (e.g. Soares-Filho et al., 2004, 2006; Walker et al., 2004; Aguiar et al., 2007; Lapola et al., 2010, Leite et al. 2012; Arvor et al., 2013; Gollnow & Lakes, 2014) with emphasis on deforestation processes (Etter et al., 2006). Thus far in the Brazilian Amazon these models have not been very successful in reproducing the observed land-use change since the end of the 20th century in a complete and cogent way (Dalla-Nora et al., 2014).

As important reasons for this lack of model performance the insufficient analysis of uncertainties regarding input data and structure of the applied models were identified (Verburg et al., 2011; Wicke et al., 2012; Olofsson et al., 2013; Dalla-Nora et al., 2014; Krüger & Lakes, 2015). Sources for data uncertainties include the selected land cover map and the model drivers (e.g. crop production) which are typically derived from different statistical databases that are not necessarily consistent. Examples for uncertainties regarding model structure are different representations of the modelled processes (e.g. Alcamo et al., 2011) or the techniques used to parameterize the model (Wicke et al., 2012; Dalla-Nora et al., 2014).

When using LULCC modeling results as input for impact assessments such as GHG emissions the uncertainty involved with the choice of input data plays an important role. Earlier studies have partially neglected to take this into consideration (Galford et al., 2011; Lapola et al., 2010; Baccini et al., 2012).

This study was designed to systematically explore the sensitivity of model results to the use of (1) different initial land cover products, (2) input variables derived from the most commonly utilized databases (in respect to the study region) and (3) the variety of model parameter values resulting from different methods used for model parameterization. The sensitivities of the modeling results to the aforementioned inputs and methods lead to a range of modeling results (i.e. spatially explicit LULCC) as well as uncertainties that are adopted through the use of modeled land use data as input for subsequent impact assessment. The aim of this study is to identify the range of modeling and subsequent impact assessment results and its possible sources. Furthermore, we aim at giving recommendations as to what combination of model input data and method to estimate parameter weights might be most suitable to capture past LULCC trajectories as well as annual GHG emissions due to LULCC in respect to the study region and spatial resolution of the land use model.

2. Material and Methods

2.1. Study Area

This study focusses on the two Brazilian federal states MT and PA containing 36 municipalities that have been blacklisted as so called “priority municipalities” in terms of monitoring and repressing deforestation through stricter environmental law enforcement (MMA, 2012). These municipalities were selected as “priority municipalities” because they accounted for 45% of the Amazonian deforestation in contrast to only constituting 6.6% of the area of the municipalities that transect the Amazon biome in Brazil. The study area comprises 2,159,971 km^2 with 1,253,165 km^2 situated in the federal state of PA and 906,807 km^2 situated in the federal state of MT.

In MT, the southern of the both examined federal states accommodating a population of 3.2 Mio. inhabitants (IBGE, 2013), 6,980,690 ha of land area is used for soybean cultivation (IBGE, 2015) and 114,900 ha were deforested in 2013 (which constitutes an increase of 52% in comparison to the area deforested in 2012) (INPE, 2013). Another dominant land use sector is cattle ranching with a herd size of 28.4 Mio. animals (IBGE, 2015). MT hosts Brazil’s largest cattle herd and is the largest producer of soybean in Brazil. Here the expansion of area used for soybean cultivation and cattle ranching could be identified as the number one cause of conversion of land with natural vegetation cover, mainly in the Cerrado biome (Greenpeace-Brazil, 2009; Barona et al., 2010).

In PA, with a population of 8.1 Mio. inhabitants (IBGE, 2013), only 119,686 ha of the land area are used for soybean cultivation (IBGE, 2015) but 237,900 ha were deforested in 2013 (which constitutes an increase of 37% in comparison to the area deforested in 2012) (INPE, 2013). The predominant land use sector here is cattle ranching with a herd size of 19.2 Mio. animals (IBGE, 2015). The vegetation is dominated by dense rainforest inhabited by many endemic plant and animal species (Vieira et al., 2008). Especially here a strong risk of a release of high amounts of carbon dioxide and a strong threat for prevailing biodiversity due to deforestation can be expected (Jantz et al., 2014). This is particularly true for the corridor along the Cuiabá-Santarem highway, the most recent of the development highways which are used to acquire the agriculturally rather underdeveloped northern parts of Brazil for crop cultivation and cattle ranching (Coy & Klingler, 2008).

2.2. Data

The Moderate Resolution Imaging Spectroradiometer (MODIS) land-cover dataset (MCD12Q1) for the year 2001 (Friedl et al., 2010) and the Global Land Cover (GLC2000) dataset for the year 2000 (Bartholomé & Belward, 2005) were employed for model initialization and base map generation. MODIS utilizes 17 classes based on the International Geosphere Biosphere Program (IGBP) land cover classification system (Wickland, 1991) while GLC2000 land-cover data is aggregated from regional land cover classes using the Land Cover Classification System (LCCS) and utilizes 22 classes. MODIS land-cover data for the year 2010 were used for the purpose of model performance assessment. Due to the lack of GLC2000 land-cover data for the year 2010 we decided on using data from the GLC2000 successor GlobCover (Bicheron et al., 2008), to assess model performance of GLC2000-based modeling runs as it intends to update and complement the GLC2000 land-cover dataset. GlobCover is also based on the LCCS.

Human population density for each cell was derived from the population density data set published by Salvatore et al. (2005). Moreover the model input comprises spatial datasets in regard to terrain slope, river and road network as well as protected areas used for the suitability analysis. Grid level information on terrain slope is based upon the SRTM30 data set (Farr & Kobrick, 2000). Information on the river network and the road network were derived from Banco de Nomes Geográficos do Brasil database (IBGE, 2012). Spatial data sets with the location of military areas, ecological and indigenous protected areas were provided by the ZONEAMENTO ecológico-econômico da área de influência da Rodovia BR-163 (Cuiabá-Santarém) (Embrapa Amazônia Oriental, 2008) and the Ministério do Meio Ambiente (MMA, 2013), respectively. Crop yields and biomass productivity of pasture were calculated with the Lund-Potsdam-Jena managed Land (LPJmL) model (Bondeau et al., 2007) on a 0.5° raster for current climate conditions (averaged over the reference period 1971-2000). Data on monthly precipitation, air temperature, cloud cover, and frequency of wet days were taken from the CRU TS 2.1 dataset (Mitchell & Jones, 2005). Additional datasets (soil texture, soil moisture, and atmospheric CO_2-concentration) were applied according to Sitch et al. (2003). An evaluation of the LPJmL modeling results can be found in Lapola et al. (2009). The simulation results from LPJmL were converted to the 900x900 m raster by assigning the respective values to all cells located within each 0.5° cell.

The data used to drive the magnitude of LULCC were taken from two commonly utilized databases for socio-economic statistics. On the regional scale (municipality level), data concerning crop production and cropland area was taken from the municipal livestock and agricultural production survey for the years 2000, 2005 and 2010 available at the IBGE database (IBGE 2015). On the country scale data regarding crop production and cropland area was taken from the FAOSTAT database (FAO 2013). As mentioned, these data were only available for the whole of Brazil. Since our land use model operates on the regional scale (federal state level), these data had to be downscaled to be available as model input. For this purpose we adapted the FAO production statistics according to the ratio of crop specific area used for agricultural production in Brazil (IBGE 2015) to the crop specific area used for agricultural production in each of the considered federal states (IBGE 2015). We used an aboveground biomass map (Leite et al. 2012) as a proxy for carbon content. The authors compiled information from the literature to create an original biomass map for the whole extension of Brazil. For the Amazon, biomass density (Tonnes/ha) values were obtained from Nogueira et al. (2008) for forest types and from Fearnside et al. (2009) for savannah vegetation. Table 2-1 summarizes all data used to initialize and operate the land use model.

Table 2-1: Datasets used for land-use modelling

spatial scale	input variable	temporal coverage	purpose	comment	source
federal state	crop production	2000-2010		production of major crops per federal state	IBGE 2015; FAO 2013 (adapted)
	livestock numbers	2000-2010		number of livestock (cattle, goat, sheep) per federal state	IBGE 2015; FAO 2013 (adapted)
	crop area	2000-2010		crop area of major crops per federal state	IBGE 2015; FAO 2013 (adapted)
	Population	2000-2010		total population number per federal state	IBGE, 2013
Grid, 30 arc-minutes cell	crop yields/ grassland NPP	2000-2010	biomass productivity; preference ranking	yield distribution of major crops	Bondeau et al., 2007
Grid, 3 arc-minutes cell	livestock density	2000	initial state	livestock distribution	Wint& Robinson, 2007
Grid, 900x900m cell	land cover	2000; 2001;2005; 2010	initial state	map of agricultural area and natural land cover types	Friedl et al., 2010 (MODIS), Bartholomé & Belward, 2005 (GLC2000)
	land cover	2005;2010	validation	map of agricultural area and natural land cover types	Bicheron et al., 2008 (GlobCover)
	population density	2000	initial state	Poverty Mapping Urban, Rural Population Distribution	Salvatore et al., 2005
	terrain slope; elevation	2000	preference ranking	SRTM30 (Shuttle Radar Topography Mission Global Coverage)	Farr & Kobrick, 2000
	river network density	2000		Banco de Nomes Geográficos do Brasil	IBGE, 2012
	infrastructure density (road infrastructure)	2000	preference ranking	Banco de Nomes Geográficos do Brasil	IBGE, 2012 (GIS calculation)
	travel distance	2000	preference ranking	distance to markets (major cities)	ESRI, 2000 (GIS calculation)
	conservation areas	2000	land use constraint	military, ecological and indigenous protected areas	military: Embrapa Amazônia Oriental, 2008; ecological and indigenous: Ministério do Meio Ambiente (MMA, 2013)

2.3. Land-use- and land-cover change modeling

Land-use change was calculated with the spatially explicit LandSHIFT model. The model is fully described in Schaldach et al. (2011) and has been tested in different case studies for Brazil (Lapola et al., 2010; Lapola et al., 2011). It is based on the concept of land systems (Turner et al., 2007) and couples components that represent the respective anthropogenic and environmental sub-systems. In our case study land-use change is simulated on a raster with the spatial resolution of 900x900m that covers the territories of the federal states of MT and PA. Cell-level information include the state variables “dominant land-use type” and “human population density” as well as a set of parameters that describe its landscape characteristics, infrastructure density and zoning regulations (see Section 2.2).

2.4. Calculation of parameter-weights

Suitability parameters and their respective weights were used to assess the suitability of a certain grid cell for cropland or pasture expansion following equation (2-1).

$$\psi_k = \sum_{i=1}^{n} w_i * p_{i,k} * \prod_{j=1}^{m} c_{j,k} \text{ , } with \sum_{i} w_i = 1 \; and \; p_{i,k}, c_{j,k} \in [0,1] \quad (2\text{-}1)$$

The parameter-weight w_i determines the importance of each suitability parameter p_i at grid cell k, while c_j represents possible constraints for land-use conversion at the given cell (e.g. protected area). Parameters that were taken into account are infrastructure density, crop yield, terrain slope, population density, travel distance, and proximity to cropland. The choice of these suitability parameters was based on other studies thematically covering the modeling of LULCC in Amazonia (e.g. Lapola et al., 2011; Soares-Filho et al., 2006). The parameter-weights were determined separately for MT and PA, with two different approaches based on MODIS and GLC2000 respectively, resulting in 8 different parameter sets for cropland as well as pastures. The first approach is based on the analytical hierarchy process (further referred to as AHP) described by Saaty (1990). An example for its application can be found in Lapola et al. (2011). The method requires 2 maps at different points in time as input. The first is a base-map without land-use change and the second is a change-map where land-use change occurred. In the case of the MODIS-based parameter-weight calculation we used data for the year 2001 as base-map while the change-map depicts land-use change between 2001 and 2006 (change map). In contrast, for the calculation of parameter-weights based on the GLC2000/GlobCover product, the base map displays the land-cover situation in 2000 while the change map refers to the period between 2000 and 2005. In order to determine the areas used for livestock grazing in the respective base map we overlaid the land-cover map with a livestock density map

(Robinson et al., 2014). Cells at or above the Brazilian average livestock density of 0.74 head livestock per hectare (Lapola et al., 2011) were classified as pasture. Parameter weights were calculated according to the following steps: First, we determine the relative importance of each parameter p_i in relation to the others. This was accomplished by calculating the difference between the average value of parameter p_i at cells with and without land-use changes (ε_i) according to equation (2-2):

$$\varepsilon_i = \begin{cases} \frac{\alpha_i}{\lambda_i} \propto_i > \lambda_i \\ \frac{\lambda_i}{\propto_i} \propto_i < \lambda_i \end{cases}, with\ \varepsilon_i \in [1, \infty] \qquad (2\text{-}2)$$

The term α_i describes the average value of parameter p_i per grid cell on the change map and λ_i describes the average value of parameter p_i in the grid cells of a base map. The higher the ε_i value, the higher the difference between the α_i and λ_i averages and the importance of that parameter. The importance of parameter p_i (Imp_i) in respect to the other parameters is then determined by a pairwise comparison of ε_i from all parameters p_i. The last step is to normalize the comparison values for each parameter p_i to 1 following equation (2-3) resulting in a value for the weight of each parameter p_i in the co-domain from 0 to 1.

$$w_i = \frac{Imp_i}{\sum_{j=1}^{n} Imp_j} \qquad (2\text{-}3)$$

The second approach we used is the criteria importance through intercriteria correlation (CRITIC) method proposed by Diakoulaki et al. (1995). An example of its application can be found in Schaldach et al. (2013). This method involves 4 steps. The first step is to calculate the standard deviation σ for each parameter p_i in the model phase of base-map generation according to the initial land-use and land-cover situation represented by the base map. This standard deviation is an expression for the contrast intensity of each parameter p_i in respect to the other parameters. The second step is to determine the linear correlation coefficient (c_{ij}) between all parameters p_i. When these correlation coefficients are summed up according to equation (2-4), we acquired a measure of the conflict created by parameter p_i with respect to the rest of the parameters.

$$\sum_{j=1}^{n} (1 - c_{ij}) \qquad (2\text{-}4)$$

The third step is to aggregate the previously quantified information (contrast intensity and conflict) into one term following equation (2-5). This term (Inf_i) is an expression for the information carried by each parameter p_i.

$$Inf_i = \sigma_i * \sum_{j=1}^{n}(1 - c_{ij}) \qquad (2\text{-}5)$$

The fourth and last step involves the calculation of w_i for each parameter p_i. This is accomplished by normalizing the resulting values Inf_i for each parameter p_i to 1 according to equation (2-6).

$$w_i = \frac{Inf_i}{\sum_{j=1}^{n} Inf_j} \qquad (2\text{-}6)$$

2.5. Model initialization

Initialization of the model utilizes high resolution land-cover data (GLC2000: 1km; MODIS: 300m; GlobCover: 500m) and statistical data on the spatial extent of crop-specific agricultural land and pastures derived from the IBGE database (IBGE 2013). The multi criteria analysis (MCA) allocation method described by Eastman et al. (1995) is employed to allocate the crop-specific agricultural area and pasture area on the non-crop-specific cropland area (for crops) and grassland area (for pasture) of the land-cover dataset.

This is accomplished by the following steps:

- First, the land-cover dataset is resampled from its native resolution to the spatial resolution of the land-use change model (by applying a majority filter).
- Second, the most suitable cells for each crop type and pastures are identified on the basis of suitability parameters (infrastructure density, crop yield, terrain slope, population density, travel distance, and proximity to cropland) and their calculated weights (see section 2.4). Further, the suitability of a certain grid cell is also determined by its land-cover type. For instance, a grassland cell is more likely to be converted into pasture than a forest cell.

The result of the initialization process is a spatial dataset that contains information on the location and extent of specific crop types and pasture areas in addition to the original land-cover information (e.g. forests).

2.6. Model evaluation

We assessed the models performance in computing the quantity and the location of LULCC for each of the different model setup combinations (Table 2-2).

Table 2-2: model setup combinations used for this study

model setup combination	land cover product	statistical database	method used to estimate parameter weights
A1	MODIS 2001	IBGE	AHP
A2	MODIS 2001	IBGE	CRITIC
A3	MODIS 2001	FAO	AHP
A4	MODIS 2001	FAO	CRITIC
B1	GLC 2000	IBGE	AHP
B2	GLC 2000	IBGE	CRITIC
B3	GLC 2000	FAO	AHP
B4	GLC 2000	FAO	CRITIC

We compared calculated cropland area on the municipality level with observed cropland area by determining model efficiency (Nash & Sutcliffe, 1970; Loague & Green, 1991). Calculated model efficiency can cover a range of values from 1 to negative ∞. A value of 1 means a perfect agreement.

Moreover, we compared modeled land use maps to maps of observed land use on the grid level by gauging the Fuzzy Kappa statistic (Hagen-Zanker, 2006), and thus assessed the models performance to simulate the location of LULCC. The Fuzzy Kappa statistic is used to express the general agreement of two categorical raster maps. The difference between the Fuzzy Kappa statistic and many other grid-based map comparison measures is Fuzzy Kappa also giving positive credit, in terms of agreement, to cells on the basis of categories found in the neighborhood of these cells (Hagen-Zanker, 2006). A Fuzzy Kappa value of one shows a perfect agreement of two maps, while a value of below zero corresponds to the expected agreement of two maps that show no correlation with each other.

2.7. Modeling greenhouse gas emissions from deforestation

We estimated instantaneous and annual (due to decay) carbon losses and resultant GHG emissions using a bookkeeping model implemented in Dinamica EGO (Soares-Filho et al., 2009). In the case of instantaneous carbon losses, we considered that all biomass removed by deforestation is instantaneously emitted. The carbon loss estimates and bookkeeping model were parameterized as in Aguiar et al. (2012). We considered a dry biomass carbon fraction (CF) of 48%. To account for carbon losses from roots we estimated belowground biomass (BGB) as a 30% fraction of aboveground biomass.

In order to estimate annual emissions we equally distributed pristine vegetation cover losses of the period from the year 2000 to the year 2010 between the years 2001 to 2010. Carbon losses are divided into four different pools (wood, BGB, slashed, burned) and distributed in time using a simple carbon bookkeeping model (Houghton et al., 2000) as in equation 2-7.

$$Emissions\ t_n = \left(\sum_{k=t_i}^{t_n} (wood * 0.1 + elemC * 0.01 + slashed * 0.4 + BGB * 0.7) \right) + burned_{t_n} \quad (2\text{-}7)$$

First we considered that 15% of the aboveground biomass is removed for commercial purposes, and emits carbon at an exponential decay rate of 10% a year. As it is common practice in the Amazon to burn deforested material to clear the area for land use, we considered that 50% of the remaining aboveground carbon is immediately emitted by fire, releasing CO_2, CO, CH_4, N_2O, and NO in the process. Slash material left on the ground to decompose represents 48% of the remaining carbon, releasing CO_2 at a decay rate of 40% a year. Elemental carbon represents 2%, released at an exponential decay rate of 1% a year. Roots decompose at a 70% a year decay rate (Aguiar et al., 2012). Resulting CO_2-, CO-, CH_4-, N_2O-, and NO-emissions are converted into CO_2e.

3. Results

3.1. Suitability parameter weights

Table 2-3 and 2-4 show the calculated parameter weights used for the suitability analysis. The results make evident that the calculated suitability parameter weights are highly dependent on the applied calculation method and land cover product.

Table 2-3: Suitability parameter weights (cropland)

	MODIS/AHP		GLC2000/AHP		MODIS/CRITIC		GLC2000/CRITIC	
	MT	PA	MT	PA	MT	PA	MT	PA
terrain slope	0.033	0.037	0.304	0.032	0.052	0.040	0.109	0.064
proximity to cropland	0.161	0.544	0.455	0.134	0.013	0.012	0.027	0.013
population density	0.078	0.090	0.036	0.465	0.797	0.801	0.270	0.741
infrastructure density	0.460	0.204	0.055	0.214	0.046	0.026	0.096	0.030
crop yield	0.030	0.035	0.034	0.030	0.048	0.071	0.404	0.094
travel distance	0.238	0.090	0.116	0.126	0.044	0.049	0.093	0.058

Table 2-4: Suitability parameter weights (pasture)

	MODIS/AHP		GLC2000/AHP		MODIS/CRITIC		GLC2000/CRITIC	
	MT	PA	MT	PA	MT	PA	MT	PA
terrain slope	0.033	0.037	0.104	0.132	0.013	0.071	0.038	0.109
proximity to cropland	0.058	0.048	0.036	0.034	0.052	0.012	0.027	0.013
population density	0.278	0.190	0.455	0.365	0.576	0.572	0.270	0.687
infrastructure density	0.360	0.325	0.225	0.214	0.156	0.156	0.237	0.030
crop yield	0.030	0.123	0.034	0.135	0.048	0.040	0.157	0.103
travel distance	0.241	0.277	0.136	0.121	0.155	0.149	0.271	0.058

For cropland the AHP method in combination with the MODIS land cover product leads to highest weights associated with the parameters infrastructure density and travel distance in MT. In PA highest parameter weights were calculated for proximity to cropland and infrastructure density. Especially in PA these results portray the current situation since new cropland and pastures tend to be established along the roads (BR-163, Transamazonica) and in close proximity to already established cropland (Aguiar et al., 2007; Soares-Filho et al., 2006). When employing the AHP method in combination with the GLC2000 land cover product we see the highest parameter weights associated with proximity to cropland and terrain slope in MT. In the case of PA high parameter weights were computed for population density and infrastructure density. The parameter weights calculated with the CRITIC method show a different picture. The highest suitability parameter weight was calculated for population density with all other parameters only having marginal influence on the allocation of cropland. This suggests that especially areas around urban centers are likely to experience land-use conversions. The calculated parameter weights for MT based on the GLC2000 land cover product are an exception. Here we see the highest factor weights associated with the parameters crop yield and population density.

In the case of pastures we can see highest weights calculated for the parameters infrastructure density, population density, and travel distance in MT and PA when using the MODIS land cover dataset. When employing the GLC2000 land cover dataset, the weight distribution is similar with the exception of the highest parameter weight associated with the parameter population density rather than infrastructure density. A different situation can be seen for the cases where we evaluated parameter weights on the basis of the CRITIC method. Here the highest parameter weights were almost exclusively computed for the parameter population density with the exception of the GLC2000 case for MT, were we see a balanced distribution over the parameters infrastructure density, population density, and travel distance.

3.2. Evaluation of model performance and model sensitivity

As mentioned in section 2.6, we use two methods to evaluate model performance in terms of quantity and location of modeled LULCC by comparing modeled and observed data on the municipal and grid level.

Table 2-5: Calculated Model Efficiency values

Landcover	year	IBGE/AHP	IBGE/CRITIC	FAO/AHP	FAO/CRITIC
GLC2000	**2000**	0.555397	0.555393	0.555393	0.555393
GlobCover	**2010**	0.167565	0.175224	0.107319	0.094698
MODIS	**2000**	0.7067	0.414929	0.7067	0.414929
	2010	0.847783	0.028223	0.871667	0.069192

Model efficiency (ME) results are shown in Table 2-5. The highest overall model efficiency can be achieved by employing the MODIS land cover dataset with input variables derived from the IBGE or FAO database and parameter weights estimated with the AHP method. Whereas the combination of the MODIS land-cover dataset and the CRITIC method to estimate parameter weights leads to the lowest calculated ME values for all evaluated years. These results show the ineptness of mentioned combinations to be used for modeling LULCC with respect to the region and, especially, the resolution of the employed land-use change model.

In the case of using the GlobCover- and the GLC2000 land cover product, relatively low and also similar model efficiency values were calculated for all cases. Only the model efficiency values assessed for the year 2010 differ slightly from each other. Especially combinations employing FAO derived statistics show model efficiency values of 0.1 for the evaluated year

2010. Model setup combinations employing the GlobCover land cover dataset produce results that do not help to reflect actual dynamics.

For this study, we compared modeled maps for the years 2000 and 2010 with the satellite derived land cover maps (MODIS, GLC2000/GlobCover) in order to quantify the agreement of modeled land use patterns to observed land use patterns on the grid level employing the Fuzzy Kappa coefficient (Hagen-Zanker, 2006).

In respect to the chosen combination of land-cover information, model input source and method to estimate parameter weights we see a range of Fuzzy Kappa results from 0.799 to 0.992 for the year 2000 and from 0.412 to 0.874 for the year 2010 (Table 2-6).

Table 2-6: Calculated Fuzzy Kappa values

	IBGE				**FAO**			
	AHP		**CRITIC**		**AHP**		**CRITIC**	
Year	**2000**	**2010**	**2000**	**2010**	**2000**	**2010**	**2000**	**2010**
GLC2000	0.992		0.992		0.992		0.992	
GlobeCover2009		0.475		0.473		0.461		0.412
MODIS2001	0.799		0.799		0.799		0.799	
MODIS2010		0.855		0.547		0.874		0.546

The general agreement is higher for the maps calculated on the basis of parameter weights estimated with the AHP method for all land cover products and model input sources in question. Furthermore, we found that when using FAO crop production and area statistics to drive the model, higher Fuzzy Kappa values were attained when working with the MODIS land cover products. In the case of the GLC2000/GlobCover land cover products, slightly higher Fuzzy Kappa values were calculated for the cases where we used IBGE statistical data as model input. The highest overall Fuzzy Kappa values were realized when using the MODIS land cover product in combination with FAO or IBGE input data and the AHP method to estimate factor weights.

3.3. Greenhouse gas emissions from land-use and land-cover change

Figure 2-1 shows that modeled LULCC between 2000 and 2010 differs in magnitude and spatial allocation. In regard to the spatial distribution of LULCC, a strong focus on grassland/shrubland vegetation types along the eastern border of PA can be observed for the cases in which LULCC was modeled on the basis of the GLC/GlobeCover land-cover product. In the case of modeled land-use on the basis of MODIS land-cover we see a more diverse distribution, especially along the development highways (BR-163, Transamazonica). In MT, we see the most obvious difference in the central northern to central western region. When modeling LULCC based on the GLC/GlobeCover land-cover product, cropland is spread along the northern border to PA, especially focusing on the northern central region. When modeling LULCC on the basis of the MODIS land cover product, cropland is more focused on the central and central western region of MT.

Figure 2-1: modeled land-use maps (2010)

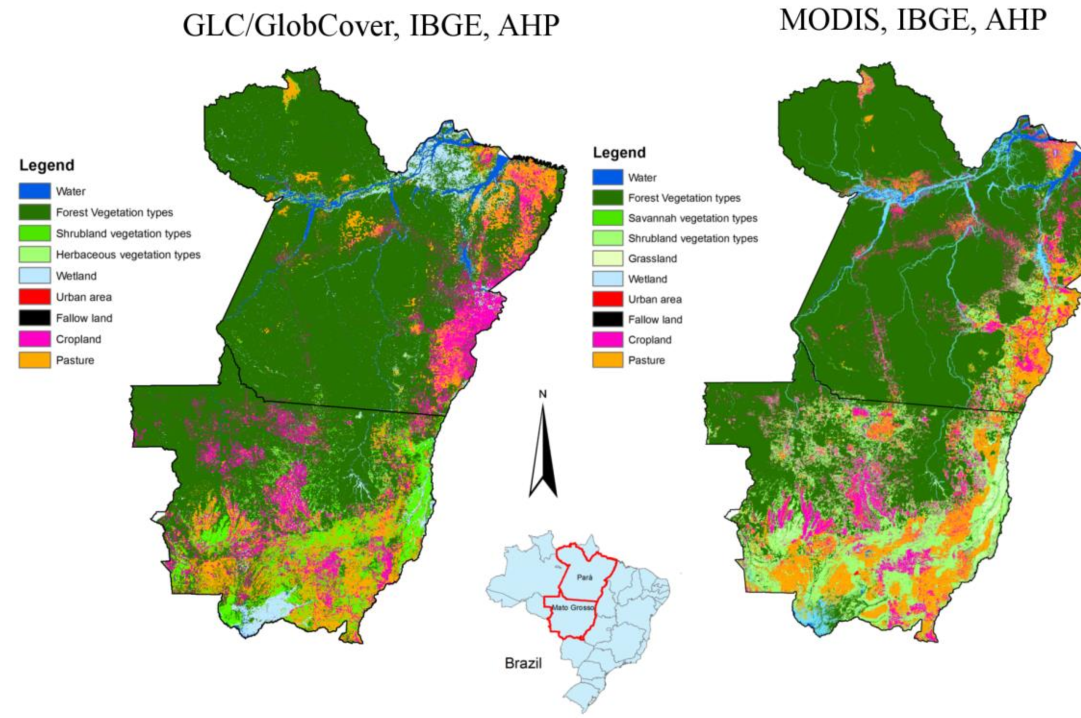
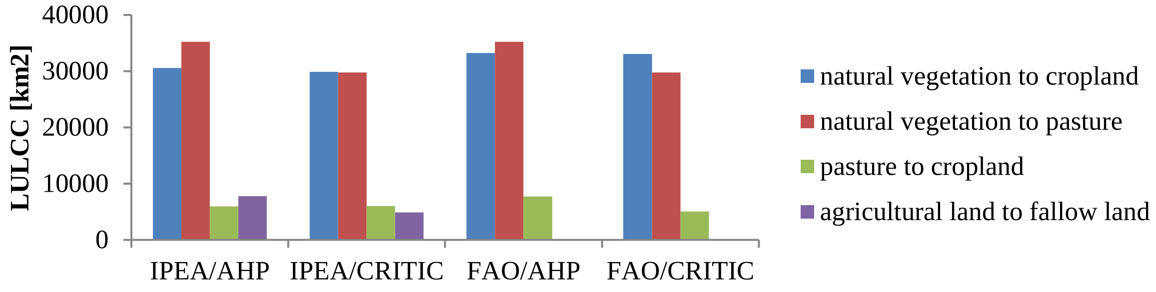


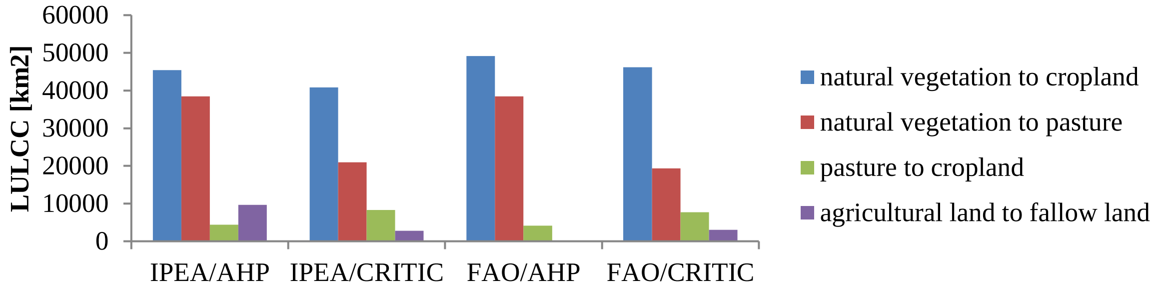
Figure 2-2 summarizes land-use change statistics for the cases employing the GLC2000/GlobCover land cover data sets. Here LULCC varies between 65,702 km^2 to 76,160 km^2. The area of newly established cropland ranges from 29,901 km^2 to 33,210 km^2 while pasture was newly established on an area between 29,775 km^2 to 35,223 km^2. An area ranging from 5,028 km^2 to 7,728 km^2 was converted from pasture to cropland and an area reaching from 4,855 km^2 to 7,804 km^2 was converted into fallow land in the cases using agricultural production statistics derived from the IBGE database. No conversion of agricultural productive land to fallow land occurred in the cases where we drove the model with production statistics derived from the FAO database.

Figure 2-2: Area affected by LULCC [km²] based on the GLC2000/GlobCover land-cover product



When employing MODIS land cover datasets we found LULCC ranging from 74,905 km² to 87,722 km² as Figure 2-3 shows. The area of newly established cropland varies between 40,870 km² to 49,166 km² while pasture was newly established on an area reaching from 19,307 km² to 38,458 km². An area of 4,141 km² to 8,345 km² was converted from pasture to cropland. An area ranging from 129 km² to 9,689 km² was converted from agricultural land to fallow land.

Figure 2-3: Area affected by LULCC [km²] based on the MODIS land-cover product



The most important input variable driven aspect of the sensitivity of modeling results is the conversion of agricultural productive land into fallow land. In the case of employing FAO derived statistics, there seems to be almost no need to convert agricultural land into fallow land due to an overachievement of agricultural production with the exception of modeling on the basis of MODIS land-cover, FAO production statistics and the CRITIC method to estimate parameter weights. The contrary applies to the cases where we drove the model with IBGE derived statistics. Here an area varying between 2,815 km² to 9,689 km² was converted into fallow land.

The method used to estimate parameter weights also impacts modeled deforestation due to differences in regard to the location of LULCC. AHP estimated parameter weights encourage the conversion of areas around the newly established highways, in general covered by forest vegetation. CRITIC estimated parameter weights shift LULCC to areas around existing cropland or to areas of high population density. These areas are usually already deforested or covered by Cerrado vegetation. We calculated a mean yearly deforestation rate of 7,174 to 8,763 km² for the cases where we applied the AHP method. In the case of employing the

CRITIC method, we simulated a mean yearly deforestation rate ranging from 6,183 to 6,788 km^2.

Table 2-7: Gross annual GHG [Pg CO_2e] emissions due to LULCC

	IBGE				FAO			
	AHP		CRITIC		AHP		CRITIC	
	PA	MT	PA	MT	PA	MT	PA	MT
GLC/GlobeCover	0.2208	0.1858	0.2206	0.1629	0.2061	0.2106	0.2032	0.1862
MODIS	0.2688	0.2386	0.2357	0.1560	0.2625	0.2586	0.2291	0.1697

Table 2-7 shows that annual CO_2e-emission estimates for PA between the years 2000 and 2010 range from 0.2032 Pg/yr CO_2e to 0.2688 Pg/yr CO_2e. In MT, annual CO_2e-emission estimates for the same period vary between 0.1560 Pg/yr CO_2e to 0.2586 Pg/yr CO_2e. In general, emission estimates should be higher in PA compared to MT due to the predominant conversion of forests to agricultural productive land (cropland or pasture) in PA and other ecosystems (Cerrado and grassland) to agricultural productive land in MT. This assumption is reinforced by the deforestation rates in both federal states. While PA experienced a mean rate of deforestation of 6,618 ha per year between the years 2000 and 2010, MT lost 5,774 ha of forest per year in the same period (INPE, 2013). While the emission differences between PA and MT seem too high in the cases of modeling LULCC on the basis of the GLC/GlobeCover land-cover products (except if using FAO derived model input and AHP method), the deviation of CO_2e-emissions between PA and MT are in a reasonable order of magnitude when driving modeled LULCC with input derived from the IBGE or FAO database in combination with parameter weights calculated with the AHP method. This is also confirmed by the model evaluation results (see section 3.2) as these combinations lead to the best results in terms of model efficiency and Fuzzy Kappa value.

4. Discussion

The main difference between both employed land cover products is the amount of modeled LULCC. While simulating LULCC based on the MODIS land cover dataset we see modeled LULCC being 7% to 23% higher as in the cases where we employed the GLC2000 land cover product to initialize the model. The highest difference in terms of LULCC (23%) is discernible for the case where we used IBGE derived input data and parameter weights estimated according to the AHP method. An explanation for this is the difference of parameter weights that were calculated on the basis of observed LULCC in respect to the land-cover product. Factor weights calculated on the basis of the MODIS land-cover map lead to an allocation of simulated LULCC to regions around the newly established highways. Simulated LULCC allocated according to factor weights calculated on the basis of the GLC2000 land-cover map focusses on proximity to already established agricultural land or to areas of high population density. The areas around newly established infrastructure (highways) tend to be characterized by lower possible crop yields/net primary productivity. Therefore, more area has to be converted in order to fulfill the required agricultural production. Comparison with other studies (e.g. Spera et al., 2014) show that simulated LULCC on the basis of the MODIS land-cover product is more similar to observed LULCC compared to LULCC simulated on the basis of the GLC2000/GlobCover land-cover product.

The highest sensitivity of modeling results is discernible in respect to the method used to estimate parameter weights for the case of modeling LULCC on the basis of the MODIS land-cover product. The amount of modeled LULCC differs by 20% to 34%. Parameter weights also affect the type of natural vegetation that is converted into cropland or pastures in respect to the applied land-cover product. While CRITIC estimated parameter weights lead to an allocation of cropland onto former forest cells and pastures on former savannah cells, the picture is quite contrary in the cases where parameter weights were estimated employing the AHP method. On the one hand, this can be explained by the difference of the parameter weights themselves in respect to the applied estimation technique. On the other hand, this is explainable by differences in regard to the methods of land-cover classification of the assessed land-cover products (e.g. Giri et al., 2005; Verburg et al., 2011).

According to findings of other authors (Arvor et al., 2012; Pacheco, 2012) most of the deforested land in regions identified as so called pioneer frontiers is converted into pastures for the purpose of less intensive cattle ranching and, after a period of a few years, sold to farmers and used to grow crops in more intensified systems. Taking this information into account, it can be concluded that the land-use change dynamics experienced in the cases where we used the AHP method to estimate parameter weights seems to be the most realistic due to the preferential conversion of forest areas into pastures and other land cover types (e.g. savannah) into cropland. This finding is supported by the fact that the modeled mean annual deforestation rate is close to the observed mean yearly deforestation rate (INPE, 2013) for the period from 2000 to 2010. The calculated mean annual deforestation rate for the mentioned period in the case of employing the MODIS land cover dataset in combination with the AHP method and input variables derived from the IBGE database is 8,763 km^2. The mean yearly deforestation rate reported by the project "Monitoramento da floresta amazônica brasileira por satélite" (PRODES) amounts to 10,950 km^2 in PA and MT for the same period (INPE, 2013). This underlines the suitability of the model setup combination involving the MODIS land-cover dataset and the AHP method to model LULCC and assess resultant deforestation for the mentioned time period, region, and spatial resolution of the LULCC model.

Furthermore, the AHP method in combination with the MODIS land cover product delivers the best parameterization results in respect to the study region and resolution of the LULCC model. Calculations of parameter weights based on this combination leads to highest weights assigned to the parameters infrastructure density and travel distance in the case of MT and to parameters proximity to cropland and infrastructure density in the case of PA. These results portray the actual situation since new cropland and pastures tend to be established along the roads (BR-163, Transamazonica) and in close proximity to already established cropland or pastures (Soares-Filho et al., 2006; Aguiar et al., 2007; Lapola et al., 2010).

For the purpose of this study we chose to estimate gross (not considering uptake of CO_2) annual GHG emissions (CO_2e) because numerous studies suggest that calculated net carbon emissions are highly uncertain (e.g. Le Quéré et al., 2009; Baccini et al., 2012). By focusing on gross GHG emissions due to LULCC we eliminate the integration of another layer of uncertainty tracing back to uptake of CO_2 by the land and ocean sinks not being quantified with high enough accuracy. The choice of the initial land-cover product influences the amount of modeled LULCC. The modeled LULCC in turn is used as a basis for the assessment of resultant GHG emissions. Therefore, GHG emission results vary between 4.4% and 27.4% according to the choice of initial land-cover product. Quaife et al. (2008) show that the application of a certain land-cover product strongly affects calculated estimates of carbon fluxes. Also the integration of biomass, and thus carbon density maps (see section 2.6), impacts the amount of estimated GHG emissions due to LULCC and introduces uncertainties in this respect. These uncertainties originate from estimates that had to be made in order to generate the biomass (carbon) density map. For instance, Ometto et al. (2014) evaluated the differences between different biomass maps for the Amazon region and found great variation in biomass amounts and spatial distribution of those amounts of up to 50%. We have not assessed this source of uncertainty within this study since we focus on uncertainties in regard to modeling LULCC and uncertainties that might be adopted through the use of land use data as input for subsequent impact assessment. The biomass (carbon) density map (Leite et al., 2012) employed for this study shows a better agreement with the MODIS land-cover map than with the GLC2000/GlobeCover land-cover product. Due to this we can assume that annual GHG emission estimates based on modeling runs utilizing the MODIS land-cover product are more realistic compared to the other cases. Galford et al. (2011) reported on carbon emissions from land-use in MT for the period from 1901 to 2006. The authors developed an integrated land-use data set, combining census-based historical land-use reconstruction and remote-sensing based land-use analysis, and modeled carbon (C) emissions with a version if the Terrestrial Ecosystem Model (Felzer et al., 2004) in a resolution of 1 km^2. The authors found net (considering uptake of CO_2) C emissions for the period from 2000 to 2006 in MT to be 0.1460 Pg/yr C. We estimated gross C emissions to be in a range from 0.1220 Pg/yr C to 0.2286 Pg/yr C from the period from 2000 to 2010 with the most plausible result being 0.1568 Pg/yr C calculated on the basis of MODIS land-cover and AHP method. This finding is supported by the model evaluation as this combination of land-cover product and method to estimate factor weights produces the best evaluation results.

Summarizing, four recommendations can be made:

a. The range of LULCC modeling results as well as the variation of subsequent assessments of GHG emissions based upon modeled LULCC stress the necessity to integrate this uncertainty perspective into any LULCC modeling exercise. This can be accomplished by comparing and evaluating available and contemplable land-cover products, input data sets, and methods (i.e. for parameterization or impact assessments) in respect to the chosen study area and resolution of the applied land-use change model prior to the actual modeling procedure.
b. Environmental impact assessment results (i.e. GHG emissions on the basis of LULCC) are often presented in combination with uncertainty intervals (e.g. Harris et al., 2012; Lapola et al., 2014). Also, LULCC modeling results could be communicated in a way that emphasizes the range of LULCC that can be expected due, for instance, the applied land-cover product or model input data source (see a.).
c. Usually the discussion of modeled LULCC results and environmental impact assessments focusses on the general fit of own findings in comparison with findings of other authors. This perspective often neglects the differences of applied land-cover, model input, and methods. Therefore, the discussion focus needs to shift to a perspective where the differences of the modeling results are highlighted and presented in a form that accentuates such contrast.
d. The best combination to model LULCC for the respective region, in respect to the chosen model resolution on a regional scale is the combination of AHP method to estimate parameter weights, the MODIS land cover product and regional production and area statistics derived from the IBGE database as can be concluded from our model evaluation results. This conclusion is reinforced by comparison of our results with other studies analyzing LULCC in the study region. Spera et al. (2014), for instance, reported an

expansion of agricultural area by 25,000 km^2 in MT between 2001 and 2011. Our results show an expansion of cropland by 27,651 km^2 in MT between 2000 and 2010. One has to keep in mind that this recommendation may be true in the case of our modeling exercise but might be wrong in regard to another region or model resolution.

5. Conclusion

Our findings show that modeling LULCC dynamics based on different land-cover products and methods to estimate parameter weights on a regional scale can result in a range of modeling and subsequent impact assessment results. Capturing these dynamics depends on the choice of initial land-cover product, statistical input data source and methods used to estimate parameter weights. Therefore, it is advisable to apply an assessment of the model sensitivity and an evaluation of the chosen combination of the mentioned products and methods prior to the actual modeling exercise. Furthermore, modeling results need to be communicated and discussed in a form that allows the reader to comprehend the range of modeling results that can be expected due to the application of a certain land-cover product, statistical input source, and applied methods.

The study also demonstrates very clearly that even the most plausible of these results are not able to fully capture the specific LULCC processes in the study region. This can be explained by the simplified representation of observed characteristic LULCC processes. Dalla-Nora et al. (2014) found that “model assumptions and simplifications still prevent LULCC models from fully representing the forces that shape land use dynamics in the Amazon”. Therefore, it is necessary to further investigate in detail which specific processes lead to land-use dynamics that can be observed in this region (e.g. multi-cropping) and to integrate these processes into our LULCC model. Such an adapted LULCC model, in combination with complex and diversified social-economic scenarios, can help to fully comprehend land use dynamics and their implications in the study area.

Chapter 3: Scenarios of future land-use and land-cover change in Southern Amazonia and resulting greenhouse gas emissions from agricultural soils

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Abstract

The calculation of robust estimates of future greenhouse gas emissions due to agriculture is essential to support the framing of the Brazilian climate change mitigation policy. Information on the future development of land-use and land-cover change (LULCC) under the combination of various driving factors operating at different spatial scale-levels, e.g., local land-use policy and global demands for agricultural commodities, is required. The spatially explicit land-use change model, LandSHIFT, was applied to calculate a set of high resolution land-use scenarios for Southern Amazonia. The time frame of the analysis was 2010 - 2030. Based on the generated maps, emission coefficients were applied to calculate annual N_2O-, CH_4-, and CO_2-emissions from agricultural soils (croplands and pastures). The results indicate that future land-use pattern and the resultant greenhouse gas emissions in Southern Amazonia will be strongly determined by global and regional demands for agricultural commodities, as well as by the level of intensification of agriculture and the implementation of conservation policies.

1. Introduction

The last decades have seen Southern Amazonia characterized by the conversion of large areas of forest and Cerrado ecosystems to agricultural land (Kohlhepp 2002; Coy 2001), resulting in high CO_2-emissions from soils and vegetation in the phase of land clearing (Schmidt et al. 2011; Krogh et al. 2003), as well as substantial losses of biodiversity (Martinelli et al. 2010). In the 1990s and early 2000s, deforestation was one of Brazil's largest contributors to greenhouse gas emissions (e.g. Lapola et al. 2014). The main drivers of these land-use and land-cover changes (LULCC) were an accelerated population growth, together with an ongoing trend of urbanization, and the expansion of cropland and pastures due to an increasing global demand for fodder and energy crops, meat and timber (Godfray et al. 2010a, Godfray et al. 2010b). Agricultural land-use currently contributes ~35% to Brazil's greenhouse gas emissions (FAO 2014) in the form of N_2O and CH_4. Consequently, these processes are important drivers of global climate change.

After 2005, increasing agricultural production could be considerably decoupled from further deforestation because of (1) successful initiatives of the Brazilian government and local authorities to protect natural ecosystems (Gibbs et al. 2015; Nepstad et al. 2014) and (2) the decrease of world market prices for soybean (Hecht 2011; Nepstad et al. 2009), in combination with a further intensification of agricultural systems (Cohn et al. 2014; Macedo et al. 2012). But several authors foresee the danger that deforestation and expansion of agricultural land will increase again (e.g. Assunção et al. 2012, Malingreau et al. 2012) as soon as Brazil´s cattle agreement runs out in 2019 (Gibbs et al. 2016) and world market prices for soy and cotton eventually rise further. Therefore, the analysis of future LULCC trajectories is an essential element for framing policies that aim at reducing land-use related greenhouse gas emissions as an important means of climate change mitigation.

Land-use change models in combination with scenario techniques are suitable tools to systematically explore future LULCC trajectories (Lambin et al. 2000) because they can capture the interplay between multiple drivers such as agricultural intensification, regional governance and linkages between regional and global markets (Mietzner and Reger 2005; Veldkamp and Lambin 2001). In the last couple of years, different land-use change models were used to study deforestation processes (Arvor et al. 2013; Aguiar et al. 2007; Soares-Filho et al. 2006, 2004; Walker et al. 2004), direct and indirect LULCC due to biofuel production (Lapola et al. 2010), and the effect of climate change on agricultural expansion (Lapola et al. 2011) within the Amazon region. An overview of these studies is given by Dalla-Nora et al. (2014), who identify two main research needs. Firstly, a more detailed description of the drivers of land-use change (e.g. agricultural production) as model input in the form of scenarios and secondly, a more detailed representation of regional land-use related policies (e.g. *Soy Moratorium*, *Cattle Agreement*, and *Brazilian Forest Code*) and management practices (e.g. intensive pasture) within the models. Moreover, while there are several studies investigating greenhouse gas emissions from land-use and land-cover change such as forest clearing (e.g. Lapola et al. 2010; Fearnside et al. 2009), only few analyses also take into account emissions from agricultural soils (e.g. Galford et al. 2010).

The objectives of our study are twofold. The first is to develop a new set of land-use scenarios for Southern Amazonia that go beyond assumptions regarding deforestation and include national and international drivers of land-use change (e.g. demands for agricultural commodities and yield increases due to intensification) as well as a detailed representation of regional land-use policies (e.g. *Brazilian Forest Code).* For this, we apply the spatially explicit land-use change model LandSHIFT (Schaldach et al. 2011) to translate the scenario storylines that were developed within the CarBioCial project (www.carbiocial.de), into a set of land-use maps. The second objective is to calculate the resultant greenhouse gas emissions (CO_2, N_2O, and CH_4) from agricultural soils in order to provide insights into the potential role of future agricultural development in Brazil for climate change mitigation.

2. Material and Methods

2.1. Study Area

The study focuses on the two federal states – Mato Grosso and Pará – in Brazil (Figure A-1), which contain 36 municipalities blacklisted as so-called “priority municipalities” in terms of monitoring and repressing deforestation through an optimized monitoring system and stricter environmental law enforcement respectively (MMA 2001). These constitute only 6.6% of the area of all municipalities within the Legal Amazon (IBGE 2014), but accounted for almost 45% of deforestation within the Amazon in 2012. Hotspots of deforestation can be found around the “development highways” (BR-070, BR-158, BR-163).

Mato Grosso has an area of 907,000 km^2 and a population of 3.2 million people (IBGE 2013). 69,807 km^2 of land is used for soybean cultivation (IBGE 2015) and 1,149 km^2 was deforested in 2013, which constitutes an increase of 52% in comparison to 2012 (INPE 2013). Another dominant land-use sector is cattle ranching, with a total herd size of 28.4 million animals (IBGE 2015). Here, the expansion of area used for soybean cultivation and cattle ranching could be identified as the primary cause of conversion of natural ecosystems to agricultural land (Greenpeace-Brazil 2009; Barona et al. 2010).

Pará has an area of 1.25 million km^2 and a population of 8 million people (IBGE 2013). Only 11,969 km^2 of the land is used for soybean cultivation (IBGE 2015). In 2013, 2,379 km^2 was deforested, which shows an increase of 37% in comparison to 2012 (INPE 2013). The dominant land-use sector is cattle ranching, with a total herd size of 19.2 million animals (IBGE 2015). The natural vegetation is dominated by dense rainforest (Vieira et al. 2008). A hotspot of LULCC is along the Cuiabá-Santarem highway (BR-163), the most recent of the "development highways" used to acquire the agriculturally underdeveloped northern parts of Brazil for crop cultivation and cattle ranching (Coy and Klingler 2008).

2.2. Modelling of land-use and land-cover change

2.2.1. Model description

Land-use and land-cover change were simulated with the spatially explicit LandSHIFT model. The model is fully described in Schaldach et al. (2011) and has been tested in different case studies for Brazil (Lapola et al., 2011; Lapola et al., 2010). It is based on the concept of land-use systems (Turner et al., 2007) and couples components that represent the respective anthropogenic and environmental sub-systems. In our case study, land-use change is simulated on a raster with the spatial resolution of 900m x 900m that covers the territories of the federal states of Mato Grosso and Para. LandSHIFT simulates the spatiotemporal dynamics of settlement, cropland and pasture by regionalizing their state-level drivers to the raster level in 5-year time periods. These drivers include human population, livestock numbers, crop production, and crop yield increases due to technological change. Input on cell-level comprises the state variables "land-use type" (Table A-1) and "human population density", as well as a set of parameters that describe its landscape characteristics (e.g. terrain slope), road infrastructure, and zoning regulations.

Important elements of the scenario storylines were related to land-use policies and agricultural intensification. In order to reflect these assumptions more accurately, LandSHIFT has been modified by integrating a new agricultural land-use type and a new process that describes the further intensification of pasture management. The *Legal Intensification scenario* presumes compliance with the new *Brazilian forest code* (Soares-Filho et al. 2014). For this purpose, a new mosaic land-use type (*Mosaic "Legal Reserve"*) was implemented. This land-use type consists of 20% cropland or pasture and 80% rainforests, which reflect the requirement of the forest code to protect a certain amount of native vegetation on farms. In order to represent the intensification of pasture management described in some of the investigated scenarios, the model includes a new sub-module for calculating the increase of biomass productivity of each pasture cell per time step (specified by the parameter *intensification rate*) until a defined maximum is reached (parameter *maximum intensity*).

2.2.2. Model input data

LandSHIFT is initialized with a gridded historic land-use map representing the year 2010, which combines MODIS land-cover data (Friedl et al. 2010) and census data on the municipality level regarding cropland and pasture area (IBGE 2015). Human population density for each grid cell was derived from the population density data set published by Salvatore et al. (2005). Moreover, the model input comprises spatial datasets in regard to landscape characteristics, road infrastructure and zoning regulations. Grid level information on terrain slope is based on the SRTM30 data set (Farr and Kobrick 2000). Information on the river network and the road network were derived from the Banco de Nomes Geográficos do Brasil database (IBGE 2012). Spatial data sets with the location of military areas, ecological, and indigenous protected areas were provided by the ZONEAMENTO ecológico-econômico da área de influência da Rodovia BR-163 (Cuiabá-Santarém) (Embrapa Amazônia Oriental 2008) and the Ministério do Meio Ambiente (MMA 2013), respectively. Crop yields and biomass productivity of pasture were calculated with the LPJmL model (Bondeau et al. 2007) on a 0.5° raster for current climate conditions (averaged over the reference period 1971-2000). Data on monthly precipitation, air temperature, cloud cover, and frequency of wet days was taken from the CRU TS 2.1 dataset (Mitchell and Jones 2005). Additional datasets (soil texture, soil moisture, and atmospheric CO_2-concentration) were applied according to Sitch et al. (2003). An evaluation of the LPJmL modeling results can be found in Lapola et al. (2009). The simulation results from LPJmL were converted to the 900x900 m raster by assigning the respective values to all cells located within each 0.5° cell.

Main input data for the land-use simulations from 2010 until 2030 is provided on the state level and includes human population, crop production, crop yield increases due to technological change, and livestock numbers (see Tables A-2 - A-4). This data is specified as part of the scenarios.

2.3. Calculation of N_2O- and CH_4-fluxes from agricultural soils

We used the average N_2O-emissions reported in Meurer et al.'s (2016) review for different land-use types in Brazil. Meurer et al. (2016) showed the non-linear relation between N_2O-fluxes from soils and pasture age (years since conversion), and hence distinguished between pastures younger and older than 10 years. As we do not have information about the age of the existing pastures in the base year 2010, we consider these pastures to be older than 10 years. For the pastures established during the scenario period between 2010 and 2030, we included the age and applied the corresponding average emissions for the estimation of total annual N_2O-fluxes. For methane, cropland is reported to be a sink for atmospheric CH_4, although positive fluxes from pastures were reported by almost all references included in this study.

2.4. Calculation of CO_2-fluxes from agricultural soils

CO_2-emissions and uptake from agricultural ecosystems were derived from changes in soil organic carbon (SOC) stocks under different land-uses. These data were derived in the course of field trials conducted within the Carbiocial project (see Supporting Information 3). Soil samples were taken from 29 plots in the study region according to the methods described in the Supporting Information. To include the most common soil types of the Amazon region (Quesada et al. 2011), the analysis concentrated on Ferralsols and Acrisols. Additionally, old (> 10 years) and young (≤ 10 years) pastures and croplands were distinguished in order to capture the specific potentials to absorb or emit CO_2. The result of the analysis was a set of SOC stocks and SOC stock changes (Table 3-1) that was applied to determine annual carbon fluxes for the different land-use scenarios.

Table 3-1: Mass corrected SOC stocks and SOC stock changes for different land-use types on Ferralsol and Acrisol for topsoil (0-30 cm), subsoil (30-100 cm) and the complete sampling depth (0-100 cm). N = the amount of individual sampling points; SE is the standard error. Due to mass correction the sum of topsoil SOC and subsoil SOC might not be similar to 0-100 cm.

		SOC stocks						**SOC stock changes**					
	n	**0-30 cm**		**30-100 cm**		**0-100 cm**		**0-30 cm**		**30-100 cm**		**0-100 cm**	
		Mg SOC ha^{-1}	**SE ±**	**Mg SOC ha^{-1}**	**SE ±**	**Mg SOC ha^{-1}**	**SE ±**	**Mg SOC ha^{-1}**	**SE ±**	**Mg SOC ha^{-1}**	**SE ±**	**Mg SOC ha^{-1}**	**SE ±**
Ferralsol													
Cerrado	18	57.4	1.75	66.19	1.66	127.02	2.89	-	-	-	-	-	-
Rainforest	23	55.58	3.16	67.43	2.07	124.38	4.4	-	-	-	-	-	-
Young pasture (≤ 10 yr)	18	52.38	3.68	59.92	1.38	114.69	4.76	-3.61	368	-9.39	1.38	-14.88	4.82
Old pasture (> 10 yr)	50	54.45	1.53	60.15	1.66	118.16	2.58	-1.64	1.61	-4.96	1.78	-5.29	2.61
Young crop-field (≤ 10 yr)	36	47.28	1.79	57.85	1.91	108.21	3.46	-6.42	1.77	-8.3	1.8	-13.28	3.36
Old crop-field (> 10 yr)	32	58.39	1.26	70.23	1.18	131.79	2.12	3	0.81	7.65	0.92	12.7	1.37
Acrisol													
Rainforest	27	34.85	1.84	41.08	2.37	77.68	3.42	-	-	-	-	-	-
Young pasture (≤ 10 yr)	9	39.64	2.65	52.59	1.19	93.41	3.34	6.1	2.65	9.46	1.19	14.95	3.36
Old pasture (> 10 yr)	27	39.17	1.14	41.27	1.62	83.38	1.7	5.13	1.14	0.23	1.48	5.41	1.62
Young crop-field (≤ 10 yr)	9	29.17	2.33	34.87	2.05	64.46	4.42	-4.47	2.33	-7.67	2.05	-12.94	4.42

2.5. Scenario storylines and model drivers

An important outcome from the CARBIOCIAL project was a set of four scenarios that describe plausible future development pathways of Southern Amazonia until the year 2030. Each scenario includes a qualitative part (storyline) that provides a short narrative of the future world, and quantitative information that describes the respective main drivers of LULCC. Input data for the LandSHIFT simulations provided by each scenario include human population (Table A-2), livestock numbers (Table A-3), crop production and crop yields (Table A-4), as well as assumptions regarding intensification of pasture management and environmental conservation.

The storyline of the *Trend scenario* describes a growing production of agricultural commodities in the study region. At the same time, further intensification of the agricultural sector leads to increasing crop yields. Natural ecosystems that are not located in protected areas are still converted into cropland and pasture. Migration processes lead to a strong population increase.

The *Legal Intensification* and the *Illegal Intensification scenario* are characterized by a further increase of crop production and livestock numbers due to a growing demand for these agricultural commodities from Asian countries. Crop yields increases are similar to the *Trend* *scenario*. Additionally, the scenarios presume the intensification of cattle ranching as described in Section 2.2.1. In Pará, we assume an intensification rate of 4.5% per time step up to a maximum of 30%. That means that the biomass productivity of any pasture grid cell is increased by 4.5% until biomass productivity is 30% higher than in the base year. As agriculture in Mato Grosso is presumed to be more mechanized, large scale, and world market oriented (Jasinski et al. 2005; Arvor et al. 2012), we assume an intensification rate of 9% up to a maximum value of 50%. These assumptions are based on observed pasture intensification rates in Brazil. According to Wint et al. (2007) and Lapola et al. (2014), the stocking density of pastures in Brazil rose continuously from 1990 to 2010, with a total increase of 45% during that period. The two scenarios differ in respect of the assumed enforcement of environmental law. Under *Legal Intensification*, the conversion of protected areas of any kind is not allowed. In addition, we assume compliance with the *Brazilian forest code*, which implies that cropland and pasture expansion is realized as the new mosaic land-use type, leaving 80% of natural land on the newly converted grid cell intact. In contrast, the *Illegal Intensification scenario* is characterized by weak law enforcement. Here, areas under ecological conservation status are de facto available for agricultural use. Also, the compliance with the *Brazilian forest code* does not apply.

The *Sustainable Development scenario* describes a society that enjoys a social model based on participation, citizenship, an inclusive economic system with clear land titles, and strong law enforcement. Natural resources are well-protected. Due to a global shift towards a more vegetarian diet that is oriented on WHO recommendations (e.g. Srinivasan et al. 2006; Amine et al. 2002), we find a strong decrease in livestock numbers and a significant increase in crop production (soybeans, beans, fruits and vegetables) for compensating the calorie intake formerly realized by animal products. Due to less immigration from other parts of Brazil, population increase is lower than in the other scenarios.

2.6. Modelling protocol

Using the scenario drivers (see Tables A-2 – A-4) as input, the LandSHIFT model generates maps for 2010 until 2030 in 5-year time steps that depict the resulting land-use pattern. For further analysis, we aggregated the 12 crop types into the land-use class cropland, the five forest types into the class forest vegetation types (Rainforest), and the two savannah vegetation types into the class savannah vegetation types (Cerrado) according to Table A-1. Changes in location and area of the respective land-use types were determined by comparing the maps for 2010 and 2030 using GIS software.

In the second step of the analysis, we first classified cropland and pasture in the 2030 map as "new" and "old" and additionally assigned each cell in the 2010 and 2030 maps the Ferrasol and Acrisol soil type. Then, the annual N_2O- and CH_4-emissions as well as CO_2-emissions (derived from SOC stock changes) were calculated for each cropland and pasture cell in both maps using the emission coefficients described in Sections 2.3 and 2.4. In order to compare the values of emission of the greenhouse gases CO_2, N_2O, and CH_4, the emitted amounts were converted into global warming potential (GWP) [CO_2e] according to Myhre et al. (2013) in relation to a time horizon of 20 years (GWP_{CH4} = 86, GWP_{N2O} = 268).

In all of our scenarios, we assume that increases of crop yields can be achieved until 2030 by technological improvements and a more intensive management. Potential negative effects of climate change on crop yields as discussed, e.g., by Lapola et al. (2011), were not considered in the analysis. In order to investigate if climate change might hinder the further increase of crop yields, we have conducted an additional simulation study with the crop model MONICA (Nendel et al., 2011). For detailed information regarding the applied method and results regarding climate driven crop yield changes refer to Section Supporting Information 4.

3. Results

3.1. Model output

The main model output comprises the time-series of grid maps showing land-use type, as well as population and livestock densities. Figure 3-1 shows the simulated land-use maps for the base year 2010 and the scenarios in 2030. Based on these maps, aggregated information on the state-level is produced, including area quantities of each land-use type. Figure 3-2 shows the land-use and land-cover change for each of the scenarios between 2010 and 2030 and the resultant changes of annual GHG emissions. Figure 3-3 presents total global warming potential (GWP) [CO_2e] for the greenhouse gases CO_2, N_2O, and CH_4 in 2030.

Figure 3-1: Simulation results from LandSHIFT. Land-use maps of Southern Amazonia in the year 2010 and for the 4 CarBioCial scenarios in 2030. For a description of the land-use types and their aggregation see Section 2.2.1 and Table A-1.

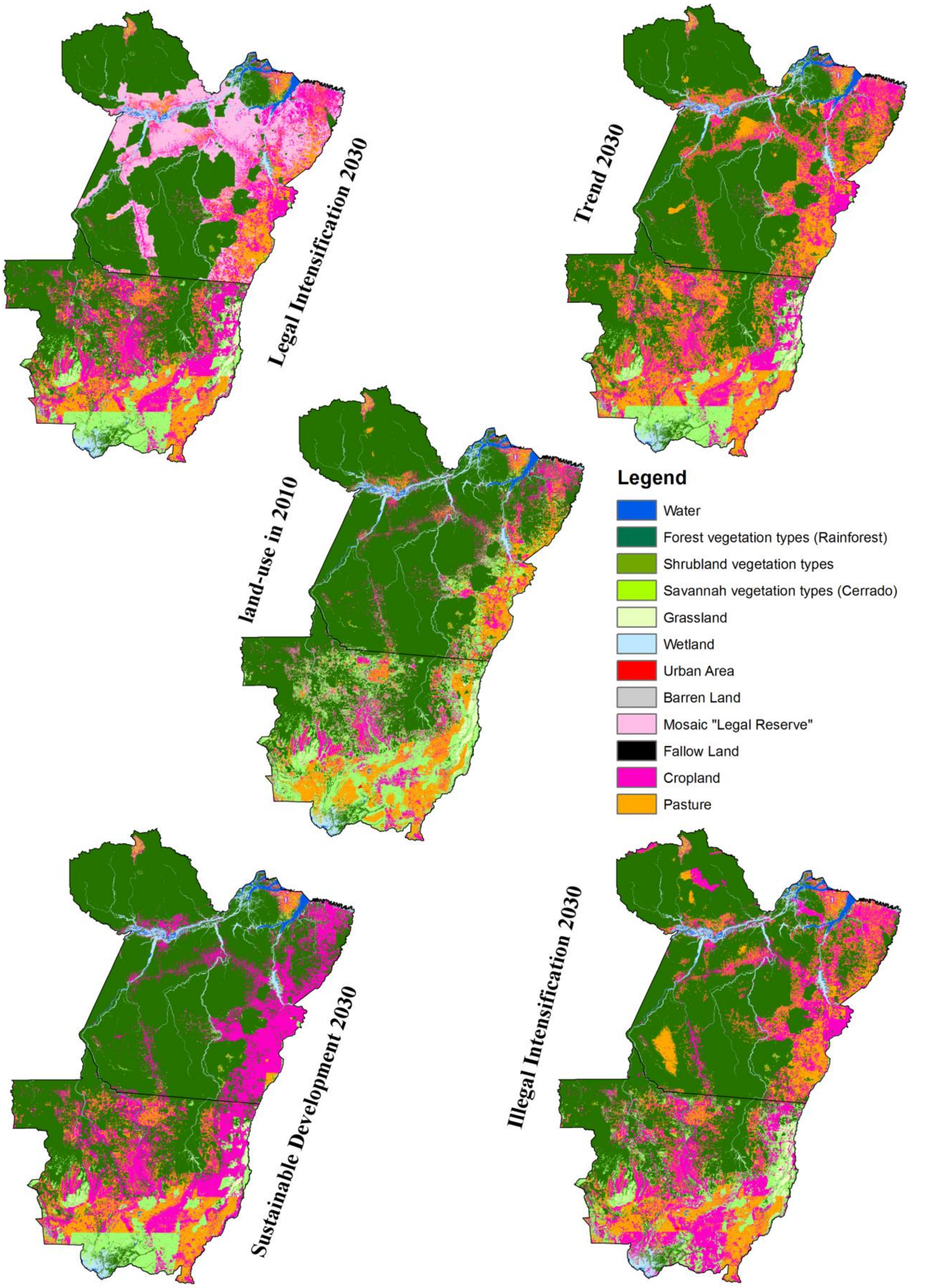
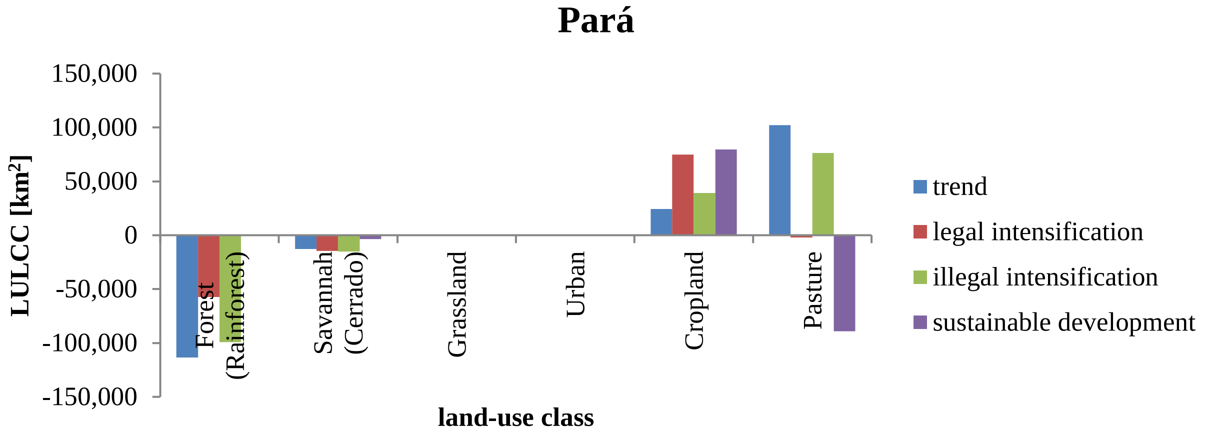
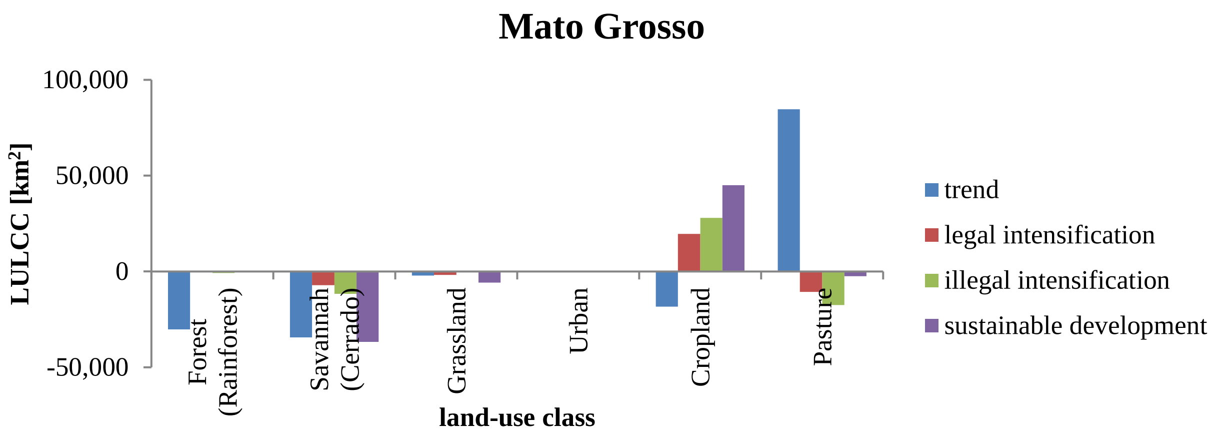
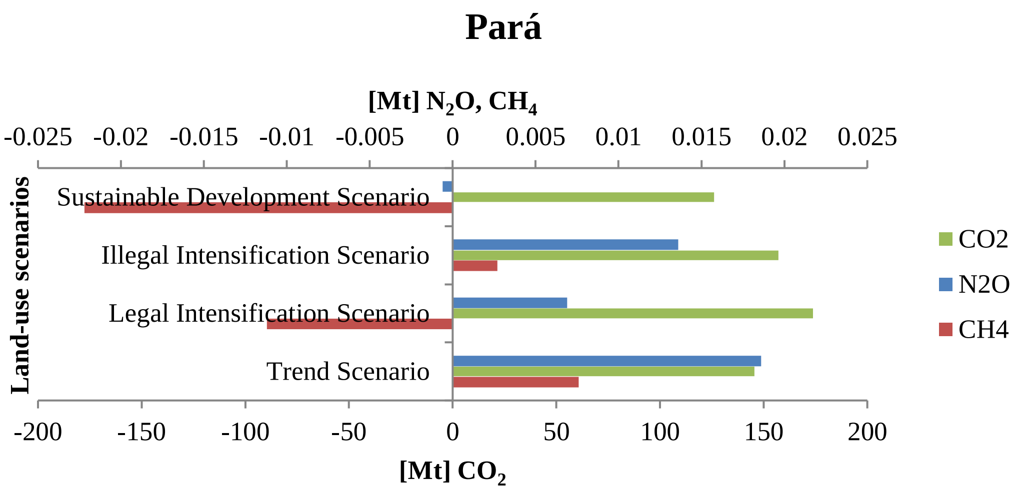


Figure 3-2: Land-use and land-cover change in Pará and Mato Grosso between 2010 and 2030 and resultant annual GHG (CO_2, N_2O, CH_4) emissions in 2030.







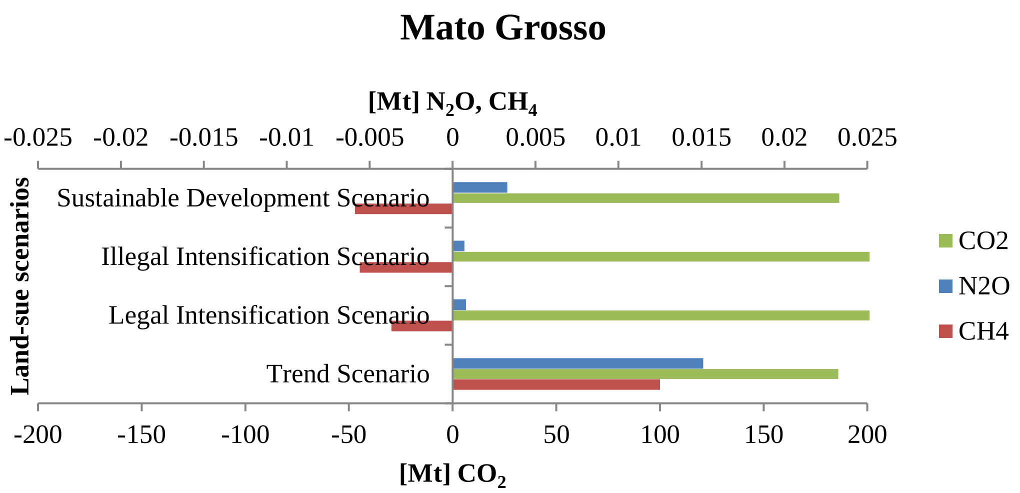
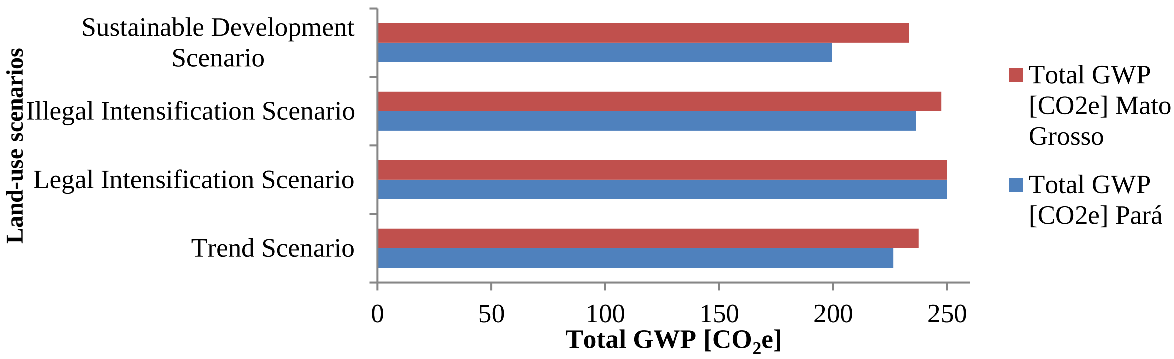


Figure 3-3: annual emissions of CO_2, N_2O, and CH4 in total global warming potential (GWP) [CO_2e] in Pará and Mato Grosso in 2030.



3.2. Trend Scenario

In Pará, the loss of tropical rainforests amounts to 113,370 km^2 (-11.5%), while 12,879 km^2 of Cerrado vegetation is converted into urban and agricultural land. The majority of deforestation can be found in close proximity to the newly established "development highways" (BR-163, BR-230) and along the eastern border of the state. The largest fraction of the converted land is used for pasture (102,271 km^2), which almost doubles in comparison to 2010. Cropland expands by 16.4%, from 147,960 to 172,190 km^2, despite the assumed yield improvements due to technological change (i.e., more efficient crop varieties; improved agricultural management). Urban area expands from 599 km^2 to 640 km^2 by 6.9%.

In Mato Grosso, 34,360 km^2 (-20.1%) of Cerrado are converted, followed by rainforest with 30,136 km^2 (-8.4%) and grassland with 2,143 km^2 (-11.1%). Most of the loss of natural vegetation can be witnessed along the BR-163 (central north-south axis) with ongoing expansion to the east and west from this starting point, along the east-west axis in southern

Mato Grosso (BR-070), and along the eastern north-south axis (BR-158). The area in central southern Mato Grosso (Pantanal) is not affected by LULCC as it is defined as a nature conservation area. Pasture area expands from 168,198 km^2 to 252,786 km^2 (+50.3%). Cropland decreases by 8.3%.

In Pará, annual N_2O-fluxes more than double due to the expansion of pasture area and cropland. In Mato Grosso, total annual emissions from pasture soils almost double between 2010 and 2030. 83% of pastures in 2030 are older than 10 years and account for 63% (0.02 Mt) of the total annual N_2O-fluxes from pasture. The slight decline in cropland leads to an emission decrease. The emission patterns are the same for methane, with the difference that most of the fluxes are negative and thus, soils are a CH_4-sink. The only exceptions are pastures, since the emission coefficient assumed accounts for CH_4-fluxes from the soil to the atmosphere. In Pará, annual CO_2-emissions from agricultural soils increase from 70.37 Mt in 2010 to 215.91 Mt in 2030. During the same period, in Mato Grosso, annual CO_2-emissions rise from 38.42 Mt to 224.43 Mt. The main contributor in both states is old cropland (> 10 years), followed by old pasture. Annual uptake by young cropland in 2030 amounts to 0.70 Mt in Pará and 3.51 Mt in Mato Grosso, respectively. Total annual CO_2-, N_2O-, and CH_4-emissions in 2030 add up to 463.9 Mt CO_2e.

3.3. Legal Intensification scenario

In Pará, 57,339 km^2 of rainforest (-5.8%) and 14,721 km^2 of Cerrado vegetation (-59.7%) are converted. Urban area increases by 6.2%, from 599 km^2 to 636 km^2. Cropland increases by 50.5%, from 134,641 km^2 to 222,677 km^2. In contrast, pasture is slightly decreasing. The results for Mato Grosso indicate a loss of 8,937 km^2 of Cerrado and grassland ecosystems. The converted area is utilized mainly for crop cultivation, with cropland increasing from 221,389 km^2 to 240,987 km^2 (+8.9 %), while pasture decreases from 168,198 km^2 to 157,536 km^2 (-6.3 %).

In both states, the decrease of pasture can be attributed to the intensification of grazing management (see Section 2.2.2), which is sufficient to absorb the additional pressure by increasing livestock numbers and therefore, seems to be a suitable tool to substantially reduce LULCC.

Due to the compliance to the *Brazilian forest code* (see Section 2.5) the resulting land-use pattern has a very different characteristic compared to the *Trend scenario* (Figure 3-1). As we have previously described, the newly allocated cropland cells have a mosaic land-cover consisting of 20% cropland or pasture and 80% of the original natural land-cover type (see

Section 2.2.1). This might have positive effects, for example on biodiversity compared to larger agricultural entities (Wright et al. 2012), but de facto means that human activities affect a larger area. Another negative side effect is that cells with potentially high crop yields can only partly be used for crop production. As a result, the production that could have been generated on this land has to be realized on additionally converted land with lower crop yields, which will lead to an over-proportionally expansion of cropland.

Total annual N_2O-fluxes slightly increase in Pará and Mato Grosso mainly due to an expansion of cropland. In contrast, annual N_2O-fluxes from pastures are slightly lower (~5 %) in 2030 as compared to 2010. This decline is more than compensated by the mentioned increase of N_2O-fluxes from cropland. At the same time, the soils' uptake of atmospheric CH_4 increases in both states, also because of an expansion of cropland. In Pará, annual CO_2-emissions from agricultural soils increase from 70.37 Mt in 2010 to 244.14 Mt in 2030. In Mato Grosso, we find an increase to 242.04 Mt. Similar to the *Trend scenario*, old cropland and old pasture are the main sources. Annual CO_2-uptake by young cropland amounts to 0.24 Mt in Pará and 4.60 Mt in Mato Grosso. Total annual CO_2-, N_2O-, and CH_4-emissions from agricultural soils in 2030 amount to 499.97 Mt CO_2e.

3.4. Illegal Intensification scenario

In Pará, 99,377 km^2 of tropical rainforest is converted. Cerrado decreases by 62.2%, from 24,648 km² to 9,327 km^2. Grassland and Cerrado diminish almost completely. Urban area spreads by 6.9%, from 599 to 640 km^2. Cropland increases by 26.5%. The scenario assumes the possibility to convert land that is under conservation (e.g. nature reserves), thus opening up spaces that are not allowed for conversion in all other scenarios. Such areas are mainly located in north-western and in north-eastern Pará on an east-west axis on the Ilha de Marajó. At the same time, we see that pressure is relieved from regions less favorable for crop cultivation (e.g. due to lower potential crop yields). Examples can be found in north-eastern Pará, east of Baía de Marajó, and in south-eastern Pará, north of the state border to Mato Grosso. Pasture expands by 74.4% mainly in the regions of south-western Pará (Parque Nacional do Rio Novo) and west of the BR-163 that are favorable for conversion due to their proximity to roads and urban centers. Further areas are acquired in the north-western region of Pará close to Bahia and to the north of Bahia. Generally speaking, the opening up of regions formerly protected due to their ecological richness leads to an increased destruction of rainforest and other natural vegetation cover.

In Mato Grosso, rainforest cover only slightly decreases by 0.2%. The largest share of land conversion is at the expanse of Cerrado vegetation, as it diminishes by 6.8%. Most of this conversion is located in southern Mato Grosso (Pantanal). Large areas are also converted along a north-south axis in central Mato Grosso and along the courses of the rivers Rio Juruena and Rio São Manuel. 9.9% of grassland vegetation is converted. Urban area is estimated to expand by 0.3%. Most of the natural vegetation cover (27,939 km^2) is converted to cropland, corresponding to an expansion by 12.6%. At the same time, pasture area decreases by 10.5%. Due to expansion of pasture taking place mainly in central southern Mato Grosso, large areas of rainforest can be spared from deforestation, e.g. along the courses of the rivers Rio Juruena and Rio São Manuel and west of the Rio Xingú along a north-south axis. This again shows the suitability of intensification measures to preserve rainforest, but also the necessity to legally protect rare and ecologically valuable zones from destruction.

In Pará, total annual N_2O-fluxes from agricultural soils increase by 68% from 2010 to 2030 due to an expansion of cropland and pasture. In Mato Grosso, total annual N_2O-fluxes amount to 0.034 Mt for 2030. This is an increase of 2.4% compared to 2010. 1.4% of total pasture emissions derive from young pastures. Uptake of atmospheric methane is reduced in Pará, but increased in Mato Grosso. While the uptake reduction in Pará is mainly driven by an expansion of pasture area, in Mato Grosso, the loss of pasture area and expansion of cropland lead to decreasing annual CH_4-emissions to the atmosphere and an increasing CH_4-uptake. Annual CO_2-emissions from agricultural soils increase to 227.14 Mt in Pará and to 239.74 Mt in Mato Grosso. Main sources are old cropland and old pasture. As a consequence of the increasing pasture area in Pará, annual emissions from young pasture also play a significant role (10.31 Mt). Again, young pastures act as a carbon sink in both states, with an annual uptake of 1.25 Mt CO_2 in Pará and of 4.33 Mt CO_2 in Mato Grosso. Total annual CO_2-, N_2O-, and CH_4-emissions equal 483.73 Mt CO_2e.

3.5. Sustainability scenario

In Pará, 3,766 km^2 of natural vegetation cover are converted into croplands. As rainforest is fully protected (see Section 2.5) the majority of the converted area (98.5%) is Cerrado vegetation. Caused by the lower meat consumption (see Section 2.5), pasture areas considerably decrease until 2030. In total, 89,038 km^2 (-86.7%) of the original pasture (2010) can be released. In contrast, cropland increases by 53.9%, from 134,641 km^2 to 227,636 km^2. Most of the newly established cropland area is found in areas that were formerly used for grazing (characterized by relatively high crop yields) and could be released due to the declining demand for meat.

Similar to the *Trend scenario*, new cropland is located in regions west of Rio Tocatins, along the “development highways” (BR-163, BR-230) and around the shores of the Amazonas in western Pará (close to Santarém).

In Mato Grosso, 36,731 km² (-21.5%) of Cerrado is lost. Also, grassland vegetation diminishes considerably, by 5,761 km² (-30.1%). Similar to Pará, rainforest area is protected (see Section 2.5) and remains constant. As expected, most of the converted area is used for crop cultivation. Consequently, cropland expands from 212,389 km² to 266,481 km² (+20.4%). Triggered by the shift in diets, pasture area is slightly decreasing.

In total, annula N_2O-fluxes are reduced by 2.9% in Pará, but increase by 10.3% in Mato Grosso. In Pará, the highest emission reduction is caused by the decrease of pasture area, whereas cropland expansion increases annual N_2O-fluxes. The increase of cropland in Mato Grosso and thus, the increase of N_2O-emissions, surmount the decrease due to a reduction of pasture area, and lead a total annual N_2O-emission increase of 10%. The total annual uptake of atmospheric methane increases by 0.022 Mt in Pará and by 0.006 Mt in Mato Grosso. The main driver in Pará is the reduced pasture area, which leads to 0.01 Mt less annual CH_4-fluxes to the atmosphere. The decrease of annual CH_4-emission in Mato Grosso is mainly resulting from an expansion of cropland that functions as a sink of atmospheric CH_4. Due to the strong expansion of cropping area, young cropland forms a significant carbon sink. Annual CO_2-uptake amounts to 29.99 Mt in Pará and 24.92 Mt in Mato Grosso, respectively. Nevertheless, in Pará, annual emissions increase to 196.50 Mt and in Mato Grosso to 224.86 Mt in 2030. The main contributor in both cases is old cropland, while emissions from pasture are lower than in the other scenarios due to the decline of pasture area. In the case of the *Sustainable Development scenario*, we calculated total annual CO_2-, N_2O-, and CH_4-emissions from agricultural soils in 2030 to be 432.70 Mt CO_2e.

4. Discussion

4.1. Differences between land-use and land-cover change scenarios

The largest reduction of rainforest was simulated for the *Trend scenario*. The main driver is the expansion of pasture. This is typical for the dynamics of pioneer frontier development in this region of Brazil, where newly deforested area is first converted into pastures, and after being used for several years, converted into cropland (e.g. Coy and Klingler 2008; Pacheco 2012). The loss of rainforest could be considerably reduced in the *Legal Intensification scenario* (compliance with the *Brazilian forest code*), indicating that, especially in Pará, effective governance and conservation of natural habitats play an important role in reducing deforestation (Arima et al. 2014). The compliance with conservation policies leads to a reduction of deforestation by 35% in the case of the *Legal Intensification scenario* in comparison with the *Illegal Intensification scenario*. These results are reinforced by Soares-Filho et al. (2010), who argues that 37% of deforestation could be halted by the establishment of new protected areas. However, especially in Pará, at the frontline of the agricultural frontier, land holders often do not acquire large parcels of land and split them into 80%/20% shares, but rather, acquire small parcels of rainforest connected to one of the development corridors. A split of these small parcels according to the regulations of the *Brazilian forest code* imposes a high risk of habitat fragmentation, which is an important factor for the loss of species diversity (Chaplin-Kramer et al. 2015). Additionally, this development does not occur from the edge of the rainforest inward, but rather, from the inside. This might lead to higher carbon losses due to the higher amount of carbon stored in the central parts of the forest compared to the forest edges (Chaplin-Kramer et al. 2015).

For both states, the highest increase of pasture area occurs in the *Trend scenario*. In this particular case, we see a strong increase of meat demand, while there is no intensification of pasture management. Consequently, the additional feed demand has to be fulfilled by further area expansion alone.

The highest increase of cropland area is projected for the *Sustainable Development scenario* for both states, which can be explained by the soaring demands for crop products due to a shift towards a healthy diet. Parts of this additional demand are fulfilled by crops (e.g. soybean) formerly used as feedstock. It is important to note that a substantial share of the newly acquired cropland is located on former pasture. Interestingly, in Pará, under the *Illegal Intensification scenario*, the expansion of cropland into protected areas leads to a considerable reduction of the total increase of cropland area. In these regions, areas with higher crop yields could be converted, thus sparing land from conversion into cropland.

The highest reduction of pasture in Pará could be achieved for the *Sustainable Development scenario* due to the lower demand for meat products. Pasture expansion under the *Legal Intensification scenario* is substantially lower than under *Illegal Intensification*. This underlines the important role of governance and for reducing area expansion, while fulfilling the growing demand for agricultural commodities, as emphasized by Soares-Filho et al. (2010). In contrast, the reduction of pasture in Mato Grosso is highest in both intensification scenarios, indicating that in this particular case, the effect of a more intensive pasture management outweighs the effect of the reduction of meat production.

Pasture intensification in Pará only leads to a reduction of pasture expansion in the case of the *Legal Intensification scenario*. The assumed intensification rate of 4.5% is too low to halt pasture expansion for the case of the *Illegal Intensification scenario*, suggesting that a higher intensification rate is necessary to completely fulfill the demand for meat products without further conversion of natural ecosystems. For Mato Grosso, a higher intensification rate was assumed, thus, expansion of pastures could be halted in the case of both intensification scenarios, indicating the need for pasture intensification as a means of habitat conservation, as has been discussed by Galford et al. (2013). We found that an increase of pasture productivity leads to a reduction of pasture area by close to 44% when comparing *Trend* and *Legal Intensification scenario* focusing on a Brazilian hotspot of cattle ranching. This result is supported by Cardoso et al. (2016), who used a Life Cycle Analysis to compare five different scenarios for beef production in Brazil, with each scenario representing a higher degree of pasture intensification. The authors found that the introduction of a forage legume on Brazilian pastures, thereby increasing the digestible biomass productivity on pastures, led to a reduction of pasture area by 36% in Brazil.

4.2. Roads to a more sustainable use of land resources in Southern Amazonia

In our scenarios, we investigated three main mechanisms that can be part of strategies aiming for a sustainable use of land resources: land conservation policies, agricultural intensification, and changing human consumption pattern.

The outstanding role of land conservation policies becomes obvious in all scenarios, as suggested by Arima et al. (2014). As the climate and soil conditions of natural ecosystems in Southern Amazonia are often very suitable for agriculture (e.g. Lambin et al. 2013, Lambin and Meyfroidt 2011), without effective conservation measures in our simulation runs, these are being converted into cropland and pasture when agricultural production increase cannot be compensated by intensification. In the scenarios, land conservation is realized either as a land-use mosaic under the *Brazilian forest code*, or by the strict protection of specific ecosystems. An analysis of the effects of these land conservation approaches on biodiversity was beyond the scope of this paper.

In Section 4.1, we elaborated on the intensification of pasture management. It plays a crucial role in reducing the area that is needed for cattle grazing. Especially in Mato Grosso, intensification was identified as a powerful instrument to stop further expansion of pasture, even under increasing livestock production (Galford et al. 2013). In the case of Pará, intensification measures were less relevant for reducing pasture expansion. Here, the compliance with environmental policies (e.g. *Brazilian forest code*) and the conservation status of natural habitats, in combination with a shift of human consumption patterns towards a more crop-based diet leading to decreasing meat consumption and decreasing livestock numbers, had the strongest impact in terms of a reduction of pasture expansion and rainforest loss.

Also, the expansion of cropland was strongly influenced by the demand for crop products and crop yield increases due to technological change and intensification of agricultural management. In both states, the largest expansion of cropland can be found in the *Sustainable Development scenario*, where it could be compensated by the drastic decline of pasture area. Interestingly, we can see a reduction of cropland area in the *Trend scenario* in Mato Grosso. This effect can be traced back to the decoupling of agricultural production and area expansion that could be witnessed over the latter half of the first decade of this century and can be explained by agricultural intensification (e.g. Gollnow and Lakes 2014; Macedo et al. 2012). However, if we assume further increase of crop production, e.g., in the *Legal* and *Illegal Intensification scenarios*, this effect is cancelled out. Furthermore, the results from the model runs with the crop model MONICA (Nendel et al. 2011) indicate that negative climate effects under an A1B emission scenario can be compensated by technological improvements. Compared to these results, the assumed yield increases in the scenarios are in a plausible range, and it is likely that climate change, at least until 2030, will not prevent further agricultural intensification. It is important to note that this situation might change by the mid- or end of this century, when changes in temperature and precipitation are projected to become more intense (e.g. Marengo et al. 2012), with potentially stronger negative impacts on crop yields (e.g. Rosenzweig et al. 2014), thus putting additional pressure on natural land resources.

Our findings are supported by Bringezu et al. (2012) and Stehfest et al. (2009), who also see changes of human consumption behavior in combination with more intensive land-use as a crucial element of avoiding further LULCC.

4.3. Agriculture and greenhouse gas emissions

In contrast to the comprehensive analysis by Galford et al. (2010) on the effect of alternative deforestation futures on greenhouse gas emissions in Mato Grosso, in this article, we focus on cropland and pasture and their role as sources or sinks of CO_2, N_2O, and CH_4. But compared to Galford et al. (2010), our study investigates a wider range of scenario assumptions and covers a larger geographic region by also incorporating the state of Pará. As our scenario analysis shows (Figure 3-2), the *Sustainable Development scenario* produces the lowest annual GHG emissions compared to the other scenarios. None of the other scenarios shows a reduction of total annual GHG emissions in 2030 compared to the *Trend scenario*. This finding again underlines the potential of a change of human consumption patterns to decrease GHG emissions from agricultural soils while, at the same time, satisfying the growing global demand for agricultural products.

In Mato Grosso, a decrease of annual N_2O-emissions from cropland is only calculated for the *Trend scenario* due to the reduction of cropland area. The *Illegal Intensification scenario* shows the lowest amount of annual CO_2-emissions from pasture as it is characterized by the lowest extent of pasture area of all scenarios due to the strong intensification of grazing management. Also, pasture expands into protected areas (mainly the Pantanal) that are characterized by higher biomass productivity, thus reducing the net area demand. Compared to the base year, we find decreasing annual CO_2-emissions from pasture for all but the *Trend scenario*. This can be explained by the increasing proportion of old pastures to young pastures, and the fact that young pastures (≤ 10 years) on Acrisols tend to emit three times more CO_2 than older pastures. Consequently, it would be a good measure to reactivate older degraded pastures instead of transforming natural vegetation in order to reduce CO_2-emissions from agricultural soils. This measure is a part of the strategies implemented in the Brazilian national Low-Carbon Agriculture (ABC) program aiming at reducing agriculture-related CO_2-emissions, while increasing agricultural productivity and assisting forest restoration (MAPA 2012)

As expected, in Pará, the largest reduction of annual N_2O- and CH_4-emissions from pasture is achieved for the *Sustainable Development scenario*. The highest increase of annual N_2O- and CH_4-emissions from pasture is calculated for the *Trend scenario,* as we assume high rates of livestock production increases, while simultaneously restricting the possibility to realize this production by means of pasture intensification. The highest increase of annual CH_4-uptake by cropland in Pará was achieved in the case of the *Sustainable Development scenario*. In Pará, the highest reduction of annual CO_2-emissions from pasture is calculated for the *Sustainable Development scenario* (-98.2%), where it can be attributed to the strong decline of area used for meat production. The highest increase of annual CO_2-emissions from pasture is calculated for the *Illegal Intensification scenario,* closely followed by the *Trend scenario*. Here, the additional emissions from an expansion of pasture area cannot be compensated by the shift of proportion of old pastures to young pastures.

For both states, a substantial increase of annual CO_2-emissions from cropland is calculated for all scenarios due to a decline of young cropland that acts as a carbon sink in favor of old cropland that acts as a source of CO_2-emissions.

An important part of our analysis is the consideration of the age of these land-use types which influences their emission behavior. This approach is comparable with the study of Galford et al. (2010), who divided pastures into young (0 – 3 years), middle (4 – 5 years), and old (≥ 6 years). However, they only use this information in regard to N_2O-emissions; in our study, we additionally focus on age-related CO_2-emissions from pastures and croplands. Furthermore, our study is based on a very broad data basis since it combines both our own observations from the specific study areas, and information from an extensive literature research.

Our results clearly indicate that the way agriculture in Southern Amazonia will develop in the coming decades not only affects the loss of natural ecosystems, but also the amount of greenhouse gas emissions from agricultural soils. Therefore, the Brazilian efforts for avoiding deforestation should be accompanied by policies aiming at a more climate-friendly agriculture.

4.4. Uncertainties and limitations of the study

Uncertainties of the simulation results can be separated into uncertainties related to the input data and uncertainties related to the structure of the model. Regarding input data quality, the disparity between different input data sources has to be mentioned. For instance, the underestimation of IBGE-based crop production data in comparison to crop area derived from MODIS satellite data. A reason for this underestimation might be the illegal agricultural activity in Brazil. A new extensive study suggests that close to 90% of Brazil´s deforestation from 2000 to 2012 was illegal (Lawson et al. 2014). This illegally cleared area was used mainly for crop production or cattle ranching. Data on crop production on these illegally cleared areas and the areas themselves are not included in the IBGE agricultural survey. Yet, MODIS satellite images capture all agricultural areas. This leads to a discrepancy of observed cropland to agricultural production concerning the land-use change model and the step of base-map generation. MODIS satellite images suggest 35% more cropland in the study area than is discernible from IBGE crop production and area statistics. This mismatch is further reinforced through the following process. In the base-map generation step, agricultural production numbers are allocated to observed cropland. If the production of agricultural commodities is underestimated, some cropland areas are left without crop production and are therefore classified as fallow land (set-aside) cells. In the next modeled time-step, these areas are used first for agricultural or pasture expansion, thus sparing areas classified as rainforest or Cerrado from deforestation. An example for model uncertainties is the simplification of agricultural management. For instance, we neglect the information that double cropping has been adapted by close to 60% of the farmers in Mato Grosso (e.g. Lapola et al. 2014). If this management practice was integrated into the model, we could expect a significantly lower pressure on land resources, as one single plot of cropland could satisfy the demand for two different crop types (e.g. soy and maize) each year. The inclusion of these processes into the land-use change model will play an important part in upcoming studies.

Furthermore, as described earlier (see Section 2.3), our estimates of annual CO_2, N_2O, and CH_4 only consider emissions caused after clearing due to persisting land use. Information on emissions caused during the conversion process, burning of biomass, or changes in biomass carbon content were neglected. So far, there is little knowledge regarding the emission of N_2O and CH_4 during the conversion process; here, further research is needed.

5. Conclusion

We have successfully developed a new set of spatially explicit land-use scenarios for Southern Amazonia and a new inventory of the related greenhouse gas emissions from agricultural soils. The generated maps have a higher spatial resolution than previous efforts with the LandSHIFT model (Lapola et al. 2010; Lapola et al. 2011) and hence, can also contribute to a further refinement of studies, for example, related to carbon emissions from deforestation and the loss of biodiversity due to land-use change (e.g. Chaplin-Kramer et al. 2015).

Since the representation of drivers of land-use change and their interplay as well as land-use policies, both in the scenarios and the applied land-use change model, is more refined than in most other simulation studies available for the Amazon region, we believe that our results can provide valuable information to scientists and policymakers alike (1) regarding the effects of particular combinations of driving factors of land-use change on greenhouse gas emissions from agricultural soils, and (2) for the development of climate change mitigation strategies and a more sustainable use of land resources.

In the light of the described limitations, the model-based scenario analysis should not be misunderstood as a method to predict concrete future events. Rather, it provides a powerful tool to systematically explore plausible constellations of social and economic drivers and the emerging trajectories and dynamics of LULCC, together with its related environmental consequences.

Acknowledgements

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Chapter 4: Assessing the effects of agricultural intensification on natural habitats and biodiversity in Southern Amazonia

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Abstract

The ongoing trend toward agricultural intensification in Latin America makes it essential to explore intensification measures in combination with assumptions regarding future socio-economic development and policies to protect biodiversity and natural habitats. Information on the future development of land-use and land-cover change (LULCC) under the combination of various driving factors operating at different spatial scale-levels, e.g., local land-use policy and global demands for agricultural commodities is required. The spatially explicit land-use change model LandSHIFT was applied to calculate a set of high resolution land-use change scenarios for Southern Amazonia. The time frame of the analysis is 2010 - 2030. The resulting maps were analyzed in combination with spatially explicit maps depicting vertebrate species diversity in order to examine the effect of a loss of natural habitats on species ranges as well as the overall LULCC-induced effect on vertebrate diversity as expressed by the Biodiversity Intactness Index in this region. The results of this study indicate a general decrease in Biodiversity Intactness in all investigated scenarios. However, agricultural intensification combined with diversified environmental protection policies show least impact of LULCC on vertebrate species richness and conservation of natural habitats compared to scenarios with low agricultural intensification or scenarios with less effective conservation policies.

1. Introduction

Human induced changes to the biosphere have caused severe losses of biodiversity (Gibson et al. 2011, Newbold et al. 2015). The process of human alteration of natural landscapes and resultant loss of biodiversity is a phenomenon that is mainly attributable to agricultural expansion and intensification. As Martinelli et al. (2010) argue, the growth of agriculture in Brazil has been accompanied by massive deforestation which is particularly true for the time period from 1970 until the end of the first decade of this century. An area of 18.8% of the original Brazilian Amazon has been deforested since 1970 (INPE 2015). Land-use dynamics in this time period in the Brazilian Amazon, being distinguished for its biodiversity-rich landscapes (Jenkins et al. 2015), have been a major threat to local terrestrial biodiversity due to the conversion of natural ecosystems into cultivated areas (Newbold et al. 2015; Chaplin-Kramer et al. 2015). Agriculture plays an important role in regard to Brazils GDP (6.1%) (World Bank Group 2016) and, more importantly, in terms of Brazils exports. A share of 39% of Brazils exported goods are agricultural commodities and products (WTO 2016). This strong contribution of the agricultural sector to Brazil's overall economic performance has had positive impacts on social prosperity in the country. According to the World Bank Group (2016), the income of 29 million people has been considerably increased, lifting them out of poverty. The inequality (measured by the Gini coefficient) has been lowered by 11% to 0.515. The income level of the poorest 40% rose by 7.1% on average compared to 4.4% income growth of the rest of the population (World Bank Group 2016). Despite these positive numbers, the global demand for agricultural products is projected to continuously rise over the coming decades (Alexandratos and Bruinsma 2012) driven by global population growth and increasing per capita demand for food, fodder, energy crops, and timber (Godfray et al. 2010a, Godfray et al. 2010b). Moreover, changes in food consumption patterns likely further enhance food demands per capita (The World Bank Group, 2016). These developments will most likely lead to further expansion and intensification of agricultural area in tropical ecosystems at the expense of natural vegetation and biodiversity (Laurance et al., 2014).

On the one hand, Grafton et al. (2015) amongst others argue that agricultural intensification (under certain conditions) may be the key for a further increase in productivity, whereby the future destruction of native vegetation can be avoided as far as possible by slowing down the spatial expansion of agriculture (e.g. Lapola et al. 2014; Cohn et al. 2014; Strassburg et al. 2014). On the other hand, some studies argue that agricultural intensification might also lead to area expansion due to the so called "rebound effect" (Baretto et al. 2013) or increasing competiveness of agriculture and, thus higher atainable revenues (Lambin & Meyfroidt 2011).

The latter may only be applicable to situations where commodities with high demand elasticity are involved (Nepstad et al. 2009).

Simulation models and scenarios are effective tools to explore current and future land-use changes and to enhance the scientific understanding of land-use change dynamics and their determinants. Many studies exist that examine land-use changes in the Amazon region by employing different models (e.g. Soares-Filho et al., 2004, 2006; Walker et al., 2004; Aguiar et al., 2007; Lapola et al., 2010, Leite et al. 2012; Arvor et al., 2013; Gollnow & Lakes, 2014). Up to now these models have not been very successful in reproducing the observed land-use changes in the Brazilian Amazon since the end of the 20th century (Dalla-Nora et al., 2014). Moreover, several studies assess the impacts of land-use changes on biodiversity in the tropics (e.g. Heckenberger et al., 2007, Gentili et al., 2014, Laurance et al., 2014, Chaplin-Kramer et al., 2015, Solar et al., 2016; Newbold et al., 2016). However, these studies focus on biodiversity in general (Heckenberger et al., 2007; Laurance et al., 2014; Chaplin-Kramer et al., 2015), on a single specific species as an indicator for biodiversity (Gentili et al., 2014; Solar et al., 2016) or on a global perspective (Newbold et al., 2016). Thereby, they cannot explicitly assess threats to the regions` overall vertebrate diversity.

This study aims to address two research questions:

- What will be the effect of a conversion of natural habitats in Mato Grosso (MT) and Pará (PA) on the distribution ranges of vertebrate species?
- What will be the effect of LULCC in MT and PA on vertebrate species diversity measured by the indicator „Biodiversity Intactness Index“?

To address research question 1 we explore the effect of a conversion of natural habitats for the timespan from 2010 to 2030 in a spatial resolution of 900m x 900m. This was accomplished for four socio-economic scenarios and three different taxa (mammals, birds, and amphibians) subdivided into three categories (threatened species, small-ranged species, and endemic species) per taxon. We decided against the inclusion of the category total species richness in our assessment. Total species richness as an indicator for biodiversity can be misleading as it is mainly driven by wide-ranged species (Colwell and Lees 2000; Jenkins et al. 2015) which might even be benefit from degraded habitats (Vale et al. 2015) while especially endemic and small-ranged species are dependent on the intactness of their respective ecosystems (Pimm et al. 1995).

To address research question 2 a pure location-based investigation of future LULCC and its possible impact on vertebrate species diversity is not sufficient. For a more exact analysis an indicator is needed. Therefore, we assessed the change of terrestrial vertebrate species abundance between the reference year 2010 and 2030 as an indicator for the effect of the different scenario assumptions (intensification, extensification, compliance with environmental law, changing consumption pattern) on vertebrate species diversity. The Biodiversity Intactness Index (BII) (Scholes & Biggs 2005) was calculated for the categories endemic species, small-ranged species, and threatened species for each considered taxon. This indicator provides information to what extent vertebrate species abundance associated with each single grid-cell (900m x 900m) is influenced by LULCC.

2. Material and Methods

2.1. Study Area

This study focusses on the two Brazilian federal states MT and PA (Figure A-1). These states differ greatly in respect to their recent agricultural developments and their level of exploitation of natural habitats due to the Brazilian agricultural development frontier running through this region (e.g. Spera et al. 2016, Dias et al. 2016).

PA has an area of 1.25 million km^2 and a population of 8 million people (IBGE 2015). Only 11,969 km^2 of the land is used for soybean cultivation (IBGE 2015). In 2015 1,881 km^2 were deforested which is about the same amount of deforestation as in 2014 (INPE 2015). The dominant land use sector is cattle ranching with a total herd size of 19.2 million animals (IBGE 2015). A hot spot of LULCC is along the Cuiabá-Santarem highway (BR-163), the most recent of the “development highways” which are used to acquire the agriculturally rather underdeveloped northern parts of Brazil for crop cultivation and cattle ranching (Coy & Klingler 2008). The natural vegetation is dominated by dense rainforest (Vieira et al. 2008) covering about 77.6% of the state’s area according to MODIS land cover data (Friedl et al. 2010). More than 40,000 vascular plant species can be found here, of which 30,000 are endemic (Vieira et al. 2008). Over 1,000 bird species are harbored in the Amazon biome (Vieira et al. 2008) as well as a high concentration of mammals, of which many are endemic, especially along the courses of the rivers crossing this biome (Jenkins et al. 2015). Of the 875 amphibian species in the country, approximately 50% are concentrated in the Amazon biome (Jenkins et al. 2015). Especially here the potential for a loss of vertebrate diversity is high due to a high density of endemic, threatened, and small ranged species (Jenkins et al. 2015) as well as ongoing and expected future agricultural expansion (Laurance et al. 2014).

MT has an area of 907,000 km^2 and a population of 3.2 million inhabitants (IBGE 2015). 69,807 km^2 of land is used for soybean cultivation (IBGE 2015) and 1,508 km^2 were deforested in 2015 which constitutes an increase of 16% in comparison to 2014 (INPE 2015). Another dominant land use sector is cattle ranching with a total herd size of 28.4 million animals (IBGE 2015). Here the expansion of area used for soybean cultivation and cattle ranching could be identified as the primary cause of conversion of natural ecosystems to agricultural land (Greenpeace-Brazil 2009; Barona et al. 2010). In comparison to PA, MT is more consolidated in terms of agricultural expansion. In recent years, the steep decline of availability of highly productive farmland, policies to curb deforestation and rising land prices have led to a development toward agricultural intensification and away from agricultural expansion (e.g. VanWey et al. 2013, Spera et al. 2014, and Cohn et al. 2014). MT is covered by two Brazilian biomes, the Brazilian Cerrado and the Amazon rainforest (e.g. Jenkins et al., 2015; Dias et al., 2016). Here, 7,000 plant species, of which 44% are endemic to the Cerrado, can be found. The Cerrado biome is especially rich in bird diversity with 837 species which resembles 49% of all bird species found in Brazil. But also 150 reptile species (50% of all Brazilian reptile species) and 180 amphibian species (28 % endemic to the Cerrado) are found here. The Cerrado biome and its waterways are home to 1,400 fish species, 40% of all fish species occurring in Brazil (Klink & Machado, 2005).

2.2. Land-use scenarios

In order to explore agricultural intensification and expansion in respect to different socio-economic and policy assumptions, 4 future scenarios have been employed for modeling land use change. These scenarios have been developed during an interdisciplinary research project (CarBioCial; www.carbiocial.de) thematically covering the study area (MT, PA). These scenarios describe plausible future development pathways of Southern Amazonia until the year 2030. Each scenario consists of a qualitative part (storyline) that provides a short narrative of the future world and a set of quantitative information that describe the respective main drivers of LULCC (Alcamo & Robeiro 2001; Alcamo et al. 2008). The storylines are elaborated by Schönenberg et al. (in revision).

The following paragraphs shortly describe the central assumptions of the scenarios. For a comprehensive overview of the quantitative scenario assumptions (crop production, crop yield, population, and livestock) see Table B-1 – B-3.

The *Trend scenario* assumes a growing demand for agrarian products which is based on an extrapolation of growth trends from 1973 to 2000 specific for each modelled crop. Furthermore, environmental policies like the Brazilian Forest Code or the Soy- and Cattle Moratorium are not part of the assumptions of this scenario. The illegal conversion of natural habitats (protected areas) is prohibited due to good law enforcement. The technological development of agricultural practices in the study area includes an intensification of agricultural production through increasing crop yields. The possibility to intensify pasture management is not considered in this scenario.

Two intensification scenarios (Legal Intensification and Illegal Intensification) assume a growing demand for agrarian products (see *Trend Scenario*) further reinforced by population and GDP growth generated in Asian countries. The technological developments of agricultural practices in the study area include a high degree of agricultural intensification including the intensification of pasture management. The intensification scenarios vary in terms of environmental law enforcement. While the *Legal Intensification scenario* assumes compliance with environmental policies (environmental protected areas, *Brazilian Forest Code*), the *Illegal Intensification scenario* presumes noncompliance with environmental law expressed as the defiance of environmental protected areas in regard to agricultural expansion and the noncompliance with the *Brazilian Forest Code*. This scenario assumes the possibility to convert land that is under conservation (e.g. nature reserves), thus opening up spaces that are not allowed for conversion in all other scenarios.

The *Sustainable Development scenario* describes a new social model. This new model includes citizenship, an inclusive economic system, clear land tenure rights, and strong law enforcement including participatory monitoring of deforestation. Furthermore, it portrays a substantial change in terms of anthropogenic consumption pattern, away from a meat oriented diet toward a healthy and sustainable diet as proposed by the WHO (e.g. Srinivasan et al. 2006; WHO 2014) including further intensification of crop production. Moreover, the conversion of areas classified as covered by rainforest into agricultural area is not allowed according to the assumptions of the scenario.

2.3. Maps of vertebrate diversity and Biodiversity Intactness Index (BII)

We use maps of vertebrate diversity covering the whole area of Brazil (Jenkins et al. 2015) to illustrate the overlapping of areas of vertebrate diversity and simulated LULCC in each investigated scenario. The species diversity maps were generated by deriving polygon range data concerning birds from BirdLife International and NatureServe (BirdLife International & NatureServe 2014) and polygon range data concerning mammals and amphibians from the International Union for the Conservation of Nature (IUCN 2014). These polygon range datasets were rendered at a spatial resolution of 10×10 km in order to produce species diversity maps considering these three groups of terrestrial vertebrates in Brazil (Jenkins et al. 2015). These groups were further subdivided into the categories small-ranged species, threatened species, and endemic species. Small-ranged species were defined as those species that have a range smaller than the median for that taxon (2,250,813 km^2 for birds, 1,230,901 km^2 for mammals, and 66,979 km^2 for amphibians) in Brazil. For example, a bird species is considered to be small-ranged by occurring naturally in a range of less than 2,250,813 km^2, which resembles the median distribution range for that taxon in Brazil. Threatened species were defined as vulnerable, endangered, or critically endangered according to the IUCN Red List (IUCN 2001). Endemic species were defined as having at least 90% of their range within Brazil and no part of their range extending more than 50 km beyond the Brazilian border. Overall, 1703 bird species, 637 mammal species and 875 amphibian species were considered in this study.

We calculated the BII accroding to Scholes and Biggs (2005) in order to assess the impact of LULCC on overall vertebarte diversity in the time from 2010 to 2030. The BII is defined as the population of a species group *i* under land-use activity *k* in ecosystem *j*, relative to a reference population on the same ecosystem type according to equation 4-1.

$$BII = \frac{\sum_i \sum_j \sum_k R_{ij} A_{jk} I_{ijk}}{\sum_i \sum_j \sum_k R_{ij} A_{jk}}$$

Equation 4-1: Biodiversity Intactness Index (Scholes and Biggs 2005)

I_{ijk}, the *"population impact"*, is the population of a certain species group *i* under land-use activity *k* in ecosystem *j*. A_{jk} is the area of land-use *k* in ecosystem *j*, R_{ij} the number of species of taxon *i* in ecosystem *j*.

Since the calculation is done on grid-cell level, each cell represents an ecosystem. The number of species is the sum of bird species, mammal species, and amphibian species assigned to one cell respectively. In order to formulate the population impact, a combination of impact values from Alkemade et al. (2009, 2013) and Biggs et al. (2008) was employed. These values indicate the reduction of mean species diversity in respect to a certain type of land-cover. The values employed are shown in Table 4-1. A BII value of 1 indicates a species abundance on the pre-colonial level. An index of 0,5 indicates that the species abundance is reduced by half in reference to the pre-colonial level.

A decreasing BII value is an expression for further reduction of biodiversity intactness due to LULCC affecting regions characterized by the occurrence of different species of different taxa. An increasing BII value expresses a recovery of biodiversity intactness mainly due to the displacement of anthropogenic land-use out of these regions or by replacement of certain land-use types by "less harmful" land-use types (e.g. cropland to fallow land) within these regions.

Table 4-1: values used as population impact to calculate BII

land-use/ land cover	population impact	source
Forest, Barren land	1.0	Alkemade et al. (2009)
Grassland, Savannah, Shrubland, Wetland	0.94	Biggs et al. (2008), Eaton et al. 2011
Fallow land	0.5	Alkemade et al. (2009)
Cropland	0.15	Alkemade et al. 2009 weighted by proportion of high input agriculture to low input agriculture in Latin America (Dikson et al. 2001)
Pasture	Pará: 0.6 / Mato Grosso: 0.3	Alkemade et al. (2013)
Mosaic Agricultural Area/rainforest (Legal Reserve)	0.83*	20% cropland impact as calculated above and 80% undisturbed forest impact (Alkemade et al. 2009)
Urban	0.05	Alkemade et al. (2009)

* A population impact value of 0.83 has been assumed for areas in the Amazon biome that are made up of 20% cropland and 80% rainforest, the so called "Legal Reserve", in which any kind of deforestation is prohibited according to the *Brazilian Forest Code* (Lei Nº 12.727 2012; Soares-Filho et al. 2014). This population impact value is considered as an expression for the fragmentation of rainforest.

2.4. Modeling and assessment protocol

LULCC was analyzed with the spatially explicit LandSHIFT model. The model is fully described in Schaldach et al. (2011) and has been tested in different case studies for Brazil (Lapola et al. 2010; Lapola et al. 2011). It is based on the concept of land-use systems (Turner et al. 2007) and couples components that represent the respective anthropogenic and environmental sub-systems. In our study, LULCC is simulated on a raster with the spatial resolution of 900m x 900m that covers the territories of the federal states of MT and PA. The LandSHIFT model generates digital maps for 2010 until 2030 in 5-year time steps that depict the resulting LULCC. For further analysis we aggregated 12 crop types (Schaldach et al. 2011) into the land-use class cropland, the 5 distributed forest types (Friedl et al. 2010) into the class rainforest, and the 2 savannah types (Friedl et al. 2010) into the class savannah (Cerrado) according to Table 4-2. Changes in location and area of the respective land-use types were determined by comparing the maps for 2010 and 2030 using GIS software.

Table 4-2: aggregation of LandSHIFT land-use classes

LandSHIFT land-use types	aggregated land-use types
evergreen needle forest, evergreen broad-leafed forest, deciduous needle forest, deciduous broad-leafed forest, mixed forest	rainforest
closed shrub land, open shrub land	shrub land
woody savannah, savannah	savannah (Cerrado)
tea, cocoa, coffee, maize, annual oil crops, pulses, rice, tropical roots and tubers, soybean, sugarcane, cassava, wheat	cropland
rangeland, pasture	pasture

As a second step, we merged the simulated land-use maps of each calculated scenario with maps of vertebrate species diversity regarding three taxa and three categories by overlaying the land-use maps with maps of vertebrate species diversity using GIS software. This promotes quantifying the impact of simulated LULCC on natural habitat area and vertebrate species diversity.

Finally, we calculated the Biodiversity Intactness Index for the reference year 2010 and 2030 according to equation 1.This was accomplished by assigning each land-use type a specific population impact (see Table 4-1) and multiplying this population impact by the area of the land-use type and the vertebrate species abundance (per taxon and category) associated with that area.

3. Results

The main model output comprises time-series of grid maps showing land-use type as well as population and livestock densities. Furthermore, aggregated information on the state-level is produced, including area quantities of each land-use type. Figure 4-1 shows the land-use and land cover change for each of the scenarios between 2010 and 2030. Figures 4-2 and 4-3 present the effect of LULCC driven loss of habitat availability per taxon and category by 2030. In addition, Tables 4-3 and 4-4 present the respective changes in the quantified BII between 2010 and 2030.

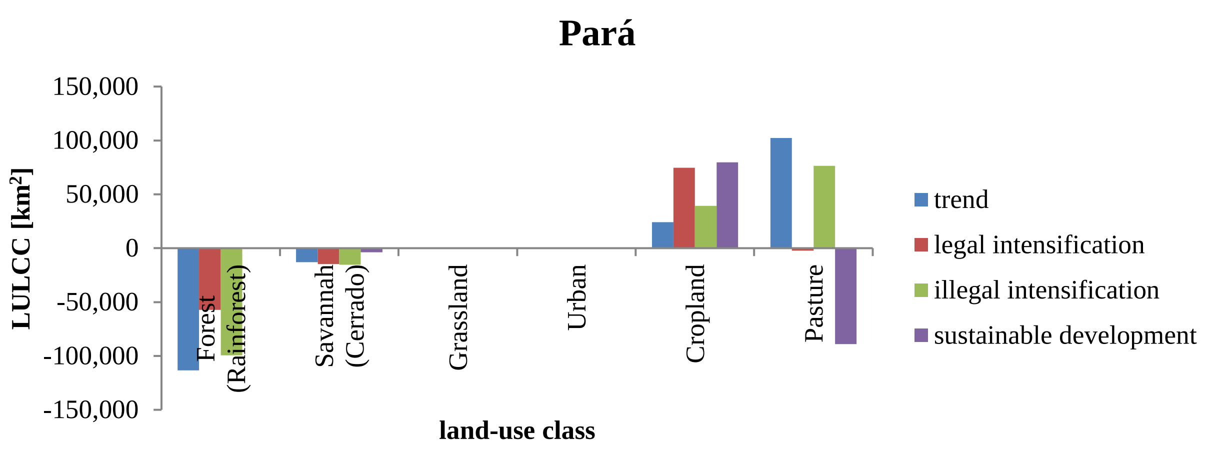
In the following the main LULCC characteristics of each scenario are described. Thereafter, the resultant effect on vertebrate species diversity is addressed by relating natural habitat area loss and vertebrate species diversity as well as by calculating the Biodiversity Intactness Index (Biggs & Scholes 2005).

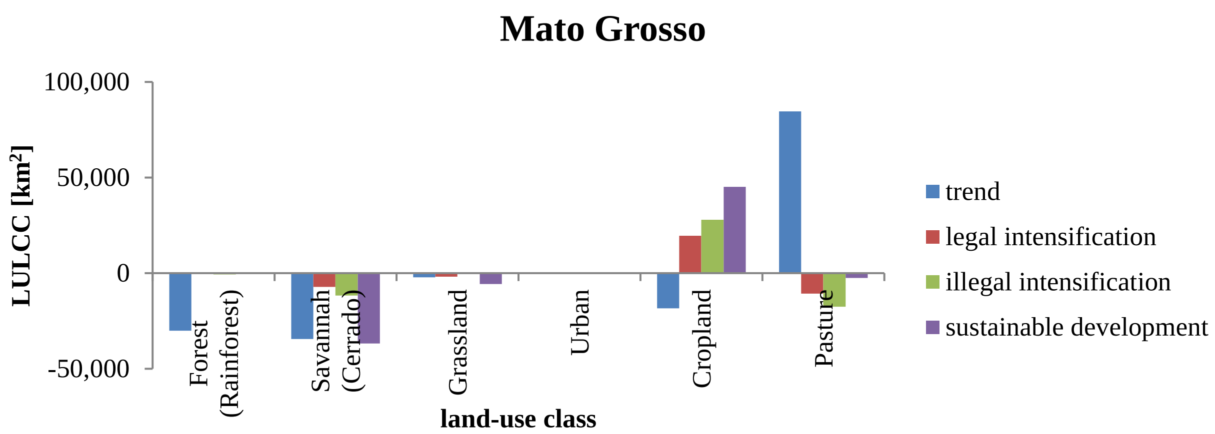
3.1. Land-use and land-cover change

3.1.1. Pará

In PA, the *Trend Scenario* leads to a loss of tropical rainforests of 113,370 km^2 (-11.5%), while 12,879 km² (-52.2%) of Cerrado vegetation is converted into urban and agricultural land (Figure 4-1).

Figure 4-1: Land-use and land-cover change in Pará and Mato Grosso between 2010 and 2030





The largest fraction of the converted land is used for pasture, which expands by 102,271 km^2 (+99.6%). Cropland expands by 24,230 km^2 (+16.4%). In the the *Legal Intensification Scenario*, 57,339 km^2 (-5.8%) of rainforest and 14,721 km² (-59.7%) of Cerrado vegetation are lost in PA. Cropland increases by 74,717 km^2 (+50.5%) and pasture areas slightly decrease by 2,238 km^2 (-2.2%). In regard to the *Illegal Intensification Scenario*, 99,377 km^2 (-10.1%) of rainforest is converted in PA. Cerrado vegetation decreases by 15,321 km^2 (-62.2%). Grassland is diminished almost completely. Cropland (+39,181 km^2, +26.5%) and pasture areas (+76,433 km^2, +74.4%) increase and cause most loss of natural habitat area. In the *Sustainable Development Scenario*, Cerrado vegetation decreases by 3,711 km^2 (-15.1%) in PA. No rainforest is converted as rainforest vegetation is fully protected (see Section 2.2). Pasture areas considerably decrease by 89,038 km^2 (-86.7%). In contrast, cropland increases by 79,676 km^2 (+53.9%). Most of the newly established cropland area is found in areas that were formerly used for grazing (characterized by relatively high crop yields). Pasture areas decline as a consequence of reduced meat demand in this scenario (see Section 2.2).

3.1.2. Mato Grosso

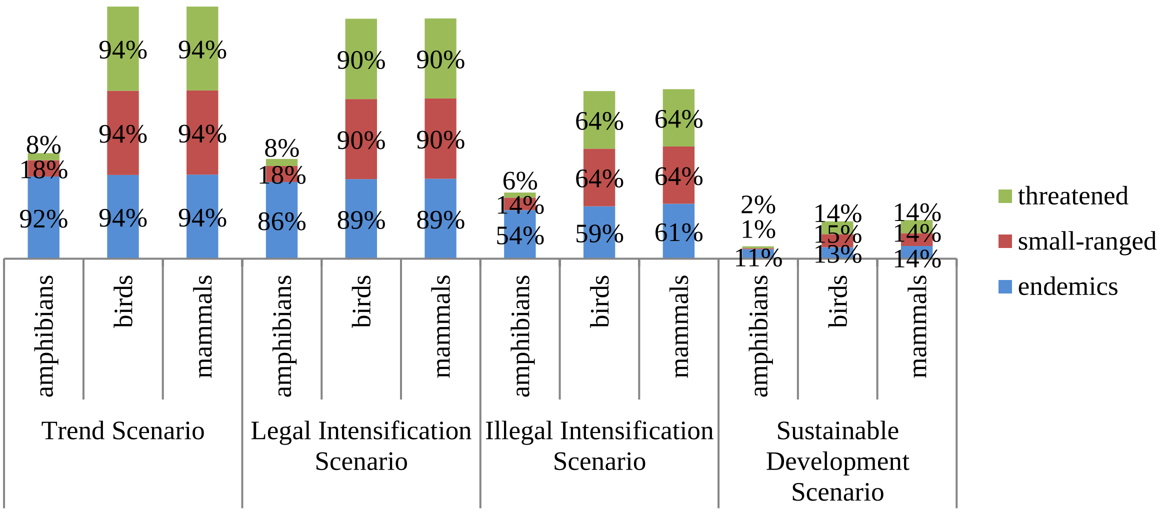
In the case of the *Trend Scenario* in MT, 34,360 km^2 (-20.1%) of Cerrado, 30,136 km^2 (-8.4%) of rainforest and 2,143 km^2 (-11.1%) of grassland area is affected by LULCC (Figure 4-1). Similar to PA, pasture area expands by 84,588 km^2 (+50.3%) and is the main driver of the aforementioned changes to natural habitat area. However, contrary to PA, cropland is simulated to decrease by 18,334 km^2 (-8.4%). The results of the *Legal Intensification Scenario* in MT indicate a loss of 8,937 km^2 (-4.2%) of Cerrado and 1,750 km^2 (-9.1%) grassland ecosystems. Rainforest area remains constant. Cropland increases by 19,589 km^2 (+8.9%), while pasture area decreases by 10,662 km^2 (-6.3%). In the *Illegal Intensification Scenario*, rainforest cover in MT decreases by only 744 km^2 (-0.2%); whereas 11,646 km^2 of Cerrado vegetation (-6.8%) and 1,890 km^2 (-9.9%) of grassland vegetation is converted. Pasture area decreases by 17,580 km^2 (-10.5%). Most of the natural vegetation cover is converted to cropland, which expands by 27,939 km^2 (+12.6%). However, 13,659 km^2 (77.7%) of the released pasture areas partially accommodate the required expansion of cropland areas. The Sustainable Development Scenario in MT leads to a reduction of Cerrado by 36,731 km^2 (-21.5%). Grassland vegetation diminishes considerably by 5,761 km^2 (-30.1%). Rainforest area is protected (see Section 2.2) and remains constant. Cropland expands by 45,092 km^2 (+20.4%). Pasture area is slightly decreasing by 2,452 km^2 (-1.5%).

3.2. Natural habitat area loss and its effect on vertebrate species diversity

3.2.1. Pará

Figure 4-2 shows that in PA, the highest impact of a loss of natural habitat area on all taxa was assessed for the *Trend Scenario*.

Figure 4-2: Loss of natural habitat area per assessed taxon and category between 2010 and 2030 in PA

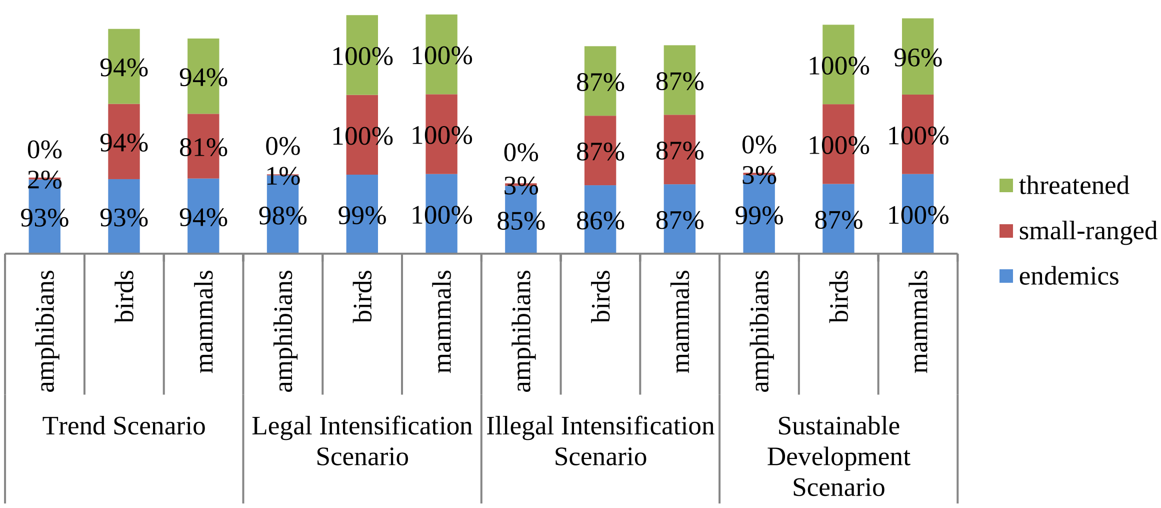


Of the 126,288 km^2 of converted natural habitats, 94% are characterized by the occurrence of endemic, small-ranged and threatened bird species as well as endemic, small-ranged, and threatened mammal species. However, the picture is a different one when looking at amphibian species. Here 92% of the converted natural habitats are also known for the occurrence of endemic amphibians, but only 18% are known to be a habitat for small-ranged amphibians and only 8% of the converted natural habitats domicile threatened amphibian species. 72,100 km^2 of natural habitats were converted in the case of the *Legal Intensification Scenario* in PA. Of this area, 90% resemble a habitat for small-ranged and threatened bird and mammal species while 89% are domiciling endemics of the taxa birds and mammals. A share of 86% of the converted area are home to endemic amphibians while 18% are known habitats of small-ranged amphibians and only 8% domicile threatened amphibians. In the case of the *Illegal Intensification Scenario*, 114,939 km^2 of natural habitat area is lost. Of this area, 59% are home to endemic bird species while 64% domicile small-ranged and threatened species of this taxon. Concerning mammal species, 61% of the converted natural habitat area domicile endemic species and 64% are known habitats of small-ranged and threatened mammal species. Amphibian species are less disturbed as 54% of the lost natural habitats are home to endemic amphibian species while 14% and 6% are domiciling small-ranged and threatened amphibian species respectively. The least negative effect on vertebrate species diversity due to a conversion of natural habitats is discernible in the case of the *Sustainable Development Scenario*. Not only the area of converted natrual habitats is less as compared to the other scenarios, also the share of this area that is a known habitat to vertebrate species is relatively low. Here, 14% of the 3,752 km^2 are home to endemic, small-ranged and threatened mammals. 13% are domiciling endemic birds, 15% are habitats of small-ranged birds and 14% domicile threatened bird species. 11% house endemic amphibians, while only 1% and 2% domicile small-ranged and threatened amphibians respectively.

3.2.2. Mato Grosso

As Figure 4-3 shows, the assumptions made for the *Trend Scenario* in MT result in a strong disturbance of vertebrate species diversity.

Figure 4-3: Loss of natural habitat area per assessed taxon and category between 2010 and 2030 in MT



An area of 66,634 km^2 of natural habitats is converted of which 93% are home to endemic bird species while 94% domicile small-ranged, and threatened bird species. 94% of the converted area is home to endemic and threatened mammals while 81% of the converted natural habitat area is a habitat for small-ranged mammal species. 93% of the converted natural habitat area are home to endemic amphibians while only 2% and 0% of this area domicile small-ranged and threatened amphibian species respectively. The latter may not be consistent with the actual situation as threatened amphibians are especially data deficient in Brazil (Jenkins et al. 2015). In the case of the *Legal Intensification Scenario*, 100% of the converted natural habitats (8,910 km^2) are domiciling small-ranged and threatened birds as well as endemic, small-ranged, and threatened mammals. 99% of the lost natural habitat area is home to endemic birds. 98% are housing endemic amphibians while only 1% are known habitats of small-ranged amphibians. Due to data deficiencies regarding threatened amphibians in Brazil, no threatened amphibian species are spatialized to the converted natural habitat area. Concerning the *Illegal Intensification Scenario*, 86% of the converted natural habitats (14,280 km^2) are considered distributions range of endemic bird species while 87% domicile small-ranged and threatened bird species respectively. Also 87% of the converted natural habitats domicile endemic, small-ranged, and threatened mammals. 85% of the converted natural area shelter endemic amphibians while only 3% are home to small-ranged amphibians. Again, no data on threatened amphibians was available in regard to the converted area in the case of the *Illegal Intensification Scenario*. The assumptions made in the case of the *Sustainable Development Scenario* lead to a reduction of natural habitats by 42,492 km^2. 88% of that area are known habitats of endemic bird species while 100% shelter small-ranged and threatened bird species. Also 100% of the converted natural habitat area domicile endemic and small-ranged mammals while 96% of the lost natural area are home to threatened mammals. 99% of the converted natural habitat area shelter endemic amphibians and only 3% are home to small-ranged amphibians. For the mentioned reasons no data concerning threatened amphibians was available for the converted natural habitats in MT.

3.3. Biodiversity Intactness Index

3.3.1. Pará

Table 4-3 shows, the impact on species diversity, as expressed by changes of the BII, is strongest as calculated in the case of the *Trend Scenario* in PA.

Table 4-3: changes of BII in Pará between 2010 and 2030 (Trend=Trend Scenario, LI=Legal Intensification Scenario, ILI=Illegal Intensification Scenario, SD=Sustainable Development Scenario)

	taxon	Trend 2010	Trend 2030	rel. Change [%]	LI 2030	rel. Change [%]	ILI 2030	rel. Change [%]	SD 2030	rel. Change [%]
Amphibians	endemic	0.79	0.71	-10.1	0.71	-10.1	0.73	-7.6	0.79	0
	small-ranged	0.65	0.52	-20	0.53	-18.5	0.57	-12.3	0.66	1.5
	threatened	0.59	0.49	-16.9	0.52	-11.9	0.53	-10.2	0.58	-1.7
Birds	endemic	0.8	0.71	-11.3	0.71	-11.3	0.73	-8.8	0.8	0
	small-ranged	0.85	0.77	-9.4	0.78	-8.2	0.78	-8.2	0.86	1.2
	threatened	0.79	0.72	-8.9	0.73	-7.6	0.75	-5.1	0.79	0
Mammals	endemic	0.79	0.68	-13.9	0.69	-12.7	0.71	-10.1	0.79	0
	small-ranged	0.86	0.77	-10.5	0.78	-9.3	0.79	-8.1	0.86	0
	threatened	0.79	0.65	-17.7	0.69	-12.7	0.72	-8.9	0.78	-1.3

We found especially strong redcutions of BII for threatened mammals, with a reduction of -17.7%, followed by threatened amphibians with a reduction of -16.9%, and endemic mammal species with a reduction of -13.9%. In the case of the *Legal Intensification Scenario*, we see BII value decreases for all taxa and categories. Especially strong disturbances can be discerned in the case of small-ranged amphibian species (-18.5%), endemic mammals as well as threatened mammals with -12.7% respectively. In the case of the Illegal Intensifcation Scenario especially small-ranged mammal species (-12.3%), endemic mammals (-10.1%), and threatened amphibian species (-10.1%) were strongly affected. Interestingly, the negative effect in the case of the *Illegal Intensification Scenario* is lower compared to the *Legal Intensification*

Scenario. The negative effects of forest fragmentation has a stronger negative impact on BII than the opening up of former protected areas for agricultural expansion. The lowest negative effect was simulated in the case of the Sustainable Development Scenario. The highest decrease was calculated for threatened amphibians (-1.7%) while the BII value for threatened mammals decreased by 1.3%. All other BII values remained constant or even increased as was the case for small-ranged amphibians (+1.5%) and small-ranged bird species (+1.2%).

3.3.2. Mato Grosso

Table 4-4 shows, the impact on species diversity in MT is more moderate in the case of the *Trend Scenario* compared to the situation in PA.

Table 4-4: changes of BII in Mato Grosso between 2010 and 2030 (Trend=Trend Scenario, LI=Legal Intensification Scenario, ILI=Illegal Intensification Scenario, SD=Sustainable Development Scenario)

	taxon	Trend 2010	Trend 2030	rel. Change [%]	LI 2030	rel. Change [%]	ILI 2030	rel. Change [%]	SD 2030	rel. Change [%]
Amphibians	**endemic**	0.67	0.62	-7.6	0.66	-1.5	0.67	0	0.62	-7.5
	small-ranged	0.56	0.54	-3.6	0.55	-1.8	0.36	-35.7	0.54	-3.6
	threatened	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Birds	**endemic**	0.66	0.6	-9.1	0.65	-1.5	0.67	1.5	0.61	-7.6
	small-ranged	0.62	0.57	-8.1	0.62	0	0.6	-3.2	0.59	-4.8
	threatened	0.59	0.51	-13.6	0.55	-6.8	0.5	-15.2	0.53	-10.2
Mammals	**endemic**	0.63	0.57	-9.5	0.62	-1.6	0.64	1.6	0.59	-6.4
	small-ranged	0.66	0.6	-9.1	0.65	-1.5	0.64	-3.0	0.63	-4.6
	threatened	0.68	0.61	-10.3	0.63	-7.4	0.6	-11.8	0.63	-7.3

Although, one has to keep in mind that the BII values in MT are on average 0.14 points below those calculated for PA due to MT being more consolidated in agricultural terms. The highest reduction of BII in Mato Grosso was simulated in the case of the *Trend Scenario*. Here, threatened bird species (-13.6%), threatened mammals (-10.3%), and endemic mammals (-

9.5%) are especially affected. In the case of the Legal Intensification Scenrio, we see a decreasing BII value for all taxa and categories with the exception of small-ranged birds which remains constant. We found especially strong decreases for threatened mammals (-7.4%) and threatened birds (-6.8%). Concerning the *Illegal Intensification Scenario*, we see decreasing BII values for all taxa and categories. Here especially small-ranged amphibians (-35.7%), threatened mammals (-11.8%) and threatened bird species (-15.3%) are strongest impacted. This effect can be explained by the opening up of former protected areas for agricultural expansion. Especially the Pantanal, known for its species richness in regard to birds and amphibians (Figuera et al. 2006; Jenkins et al. 2015), is affected by the displacement of agricultural areas into formerly protected areas. Interestingly, the Sustainable Development Scenario in MT results in a strong negative impact. It becomes obvious that all taxa and categories are affected negatively, especially endemic amphibians (-7.5%) and endemic birds (-7.6%) as well as threatened birds (-10.2%) and threatened mammals (-7.4%).

4. Discussion

Agricultural intensification has played an important role in regard to recent agricultural production growth in Brazil and is likely to further increase Brazil´s crop and beef production considerably (Pereira et al. 2012). The observed decoupling of production increases from deforestation in the latter half of the first decade of this century (e.g. Macedo 2012; Gollnow & Lakes 2014) have shown that the intensification of agricultural systems not only supports food provisioning, it also limits the expansion of agricultural area; thus the destruction of natural habitats (Latawiec et al. 2014).

This trend is confirmed in our study, which is among the first to investigate the impact of projected LULCC on a proxy for overall terrestrial vertebrate diversity on a regional scale. The negative effect of projected future agricultural production growth on natural habitats and vertebrate species diversity is considerably reduced through agricultural intensification and particularly through intensification of grazing intensities on pastures (compare with Strassburg et al. (2014) as well as Latawiec et al. (2014)). The two agricultural intensification scenarios show substantially less LULCC compared to the *Trend Scenario* based on constant crop yields and grazing intensities of the reference year 2010.

In PA, the loss of natural habitats could be reduced by 43% in the case of the *Legal Intensification Scenario* and by 9% in case of the *Illegal Intensification Scenario* compared to the *Trend Scenario*. This is also confirmed by Cohn et al. (2014) who have shown that the encouragement of an intensification of pastures, either through subsidies of intensified systems or tax on extensive pastures, considerably limits the conversion of natural habitats until 2020. Also, in these two intensification scenarios the share of the converted natural habitats that is known as habitats to vertebrate species is less as in the case of the *Trend Scenario* (see Figure 2). The strongest effect in regard to mitigating the effect of a conversion of natural habitats on vertebrate species diversity could be achieved in the Sustainable Development Scenario. Here, the loss of natural habitats could be reduced by 97% (from 126,288 km^2 to 3,752 km^2) in comparison with the *Trend Scenario*. Additionally, only 11-15% of the converted 3,752 km^2 natural areas in the Sustainable Development Scenario are known habitats of amphibian, bird, and mammal species.

In MT, the area of affected natural habitats in the case of the *Illegal Intensification scenario* could be reduced by 78% (from 66,634 km^2 to 14,280 km^2) compared to the *Trend Scenario* with 85-87% of that area domiciling vertebrate species diversity. This reduction due to agricultural intensification is surpassed by the *Legal Intensification Scenario*. Thereby, the loss of natural habitats could be limited by 86% (from 66,634 km^2 to 8,914 km^2) compared to the *Trend Scenario* with the caveat that 100% of that area is habitat to amphibian, bird, and mammal species. These results suggest that intensification measures area especially effective if combined with adequate conservation policies as assumed in the case of the *Legal Intensification Scenario* (see Section 2.2). This is confirmed by several other authors (e.g. Arima et al. 2014; Ceddia et al. 2014) who found that the intensification of agricultural production and the protection of natural habitats have the highest impact in terms of limiting the conversion of natural habitats, and thus promoting the conservation of vertebrate species diversity. The optimal combination of intensification and conservation measures in terms of a maximum reduction of converted natural habitats depends on the present situation in the respective region as the heterogeneity of losses of natural habitats in PA and MT under the respective scenario assumptions illustrates. Concerning the Sustainable Development Scenario in MT, cropland area expands especially strong due to a shift of anthropogenic consumption patterns away from meat toward crop intake while there is only a slight release of pasture area,. Therefore, the decrease of pasture area can only partially counteract the expansion of cropland, and thus the loss of natural habitat area. Overall, this leads to a reduction of converted natural habitat area by 36% compared to the *Trend Scenario* (see Figure 1). This is considerably less as compared to both intensification scenarios.

The effects of a loss of natural habitats on vertebrate species diversity are confirmed by our assessment of the BII in PA. We see decreasing BII values in the case of all simulated scenarios for all assessed taxa and categories with few exceptions (small-ranged birds and amphibians in regard to the Sustainable Development Scenario) in PA. These decreases are especially strong in the case of the *Trend Scenario* and both intensification scenarios. In the case of the *Legal Intensification Scenario*, the requirement to establish a “Legal Reserve”, a share of 80% of any holding covered by rainforest that needs to be preserved, leads to a fragmentation and consequently degradation of rainforest habitats (e.g. Laurance et al. 2002; Haddad et al. 2015). This fragmentation in turn causes a considerable reduction of the BII values in the case of the *Legal Intensification Scenario* across all assessed taxa and categories which are stronger as in the *Illegal Intensification Scenario* where a fragmentation of rainforest habitats is not assumed. The negative effect of LULCC on vertebrate species diversity as expressed by the BII is weakest in the case of the Sustainable Development Scenario. This is attributable to the effect of a substantial reduction of the global meat intake which leads to a significant reduction of pasture area, and thus overall expansion of agricultural area into natural habitats. Even without an intensification of pasture management, this reduction of pasture area is able to compensate further expansion of cropland area. Thereby, cropland expansion is limited to released pasture areas, which mitigates LULCC pressure on natural habitats.

The positive implication of agricultural intensification on biodiversity found in PA is confirmed also in MT. Here, the BII values decrease in almost all assessed taxa and categories in the case of the *Legal Intensification Scenario* and *Illegal Intensification Scenario*. This can be explained by the reduced land requirements in both scenarios. As current protected areas have no legal conservation status in the *Illegal Intensification Scenario*, loss of natural habitats is simulated in the biodiverse areas of the Pantanal. Here, Jenkins et al. 2015 found especially strong concentrations of bird and amphibian species. This explains why wemeasure especially strong decreasing BII values for allthreatened vertebrate species as well as small-ranged amphibian species in the *Illegal Intensification Scenario* in MT. In contrast, current protected areas are assumed being effectively conserved in the *Legal Intensification Scenario*, which displaces LULCC from the Pantanal to other unconserved, less biodiverse areas. This prevents strongly decreasing BII value for threatened vertebrate species and especially small-ranged amphibian species in the *Legal Intensification scenario* in MT. Moreover, the overall higher BII values in the *Legal Intensification Scenario*, compared to the *Illegal Intensification Scenario*, shows that effective conservation of existing protected areas can further enhance biodiversity in MT in 2030. Newbold et al. (2016) calculated BII values of around 70% for the Brazilian Cerrado (mainly located in MT) as well as 85% for the Amazon biome (mainly located in PA). This agrees well with our calculation for the year 2010 of 0.59-0.68 (MT) and 0.65-0.86 (PA) respectively (see Tables 3 and 4.) The fact that the estimates found in our study are slightly lower than those estimated by Newbold et al. (2016) is explained by taking into account that Newbold et al. focused on the whole Cerrado and Amzonia region while we assess a subregion that is and was characterized by especially strong LULCC dynamics.

On the one hand, the potential for agricultural intensification in the Amazon may hint at the way of sustaining food production here (e.g. Grafton et al. 2015) but, on the other hand, it also draws a distressing picture of the future in regard to negative impacts of intensification measures (Geiger et al. 2010). Despite all the positives of an intensification of agricultural production in regard to a conservation of natural habitats, the negative impacts of an intensified agriculture cannot be neglected. Especially pesticide, herbicide, and fertilizer application have to increase in order to increase grass- and cropland productivity (Satarri et al. 2016). The increased application of such products will have negative effects on biodiversity (Geiger et al. 2010). Especially the use of pesticides in tropical regions has strong negative effects on amphibian populations because they are more susceptible to pesticide use as compared to amphibian populations in temperate regions (Tscharntke et al. 2012). Therefore, biodiversity on intensified cropland is likely to decrease. Furthermore, the adoption of intensified agricultural production will cause higher costs of production. These higher costs may hinder smallholder farmers to apply such techniques. This in turn will imperil their ability to stay competitive in comparison to large land holders who have better access to monetary resources and can make larger investments into the intensification of agricultural production (Herrero et al. 2009). An increased livestock production in intensified systems (especially feedstock systems) will increase the demand for livestock fodder production which, in turn, will induce an expansion of cropland area and may be a cause of additional deforestation (Herrero et al. 2009).

4.1. Limitations and uncertainties of the study

Concerning the data that was used to assess the effect of a loss of natural habitat area on species diversity as well as the BII values, the species diversity maps (Jenkins et al. 2015), issues of data deficiency have an impact on our estimates. Especially amphibian and mammal species are understudied. Data deficient mammals are mainly concentrated in the Amazon whereas around 30% of all assessed amphibians are generally data deficient (Jenkins et al. 2015). This may lead to an underestimation of the impact of loss of natural habitats on vertebrate diversity especially in regions covered by rainforest (Amazon). Notable are threatened amphibian species. Here, only 4% of the assessed species appear to be threatened, whereas the global rate of threatened amphibians lies at 31% (Bland et al. 2014) suggesting that the high data deficiency in regard to this taxon and the investigated area are significantly influencing our results.

Moreover, we do not holistically explore the effects of agricultural intensification on natural habitats and its biodiversity. In order to do so it would require an analysis of all factors of agricultural intensification that positively or negatively influences wildlife and habitats. This analysis would have to include emissions caused due to intensification (livestock, fertilizers etc.) and their effect on biodiversity as well as indirect LULCC, for instance caused by a cropland expansion due to an increasing demand for fodder in feedstock systems. The inclusion of these factors was beyond the scope of this study.

In all of our scenarios we assume that increases of crop yields until 2030 can be achieved by technological improvements and a more intensive agricultural management alone. At the same time studies such as Lapola et al. (2011) and Oliviera et al. (2013) point out that climate change might have negative effects on crop yields in Amazonia. It is important to note that this situation might occur until the mid or end of this century when changes in temperature and precipitation are projected to become more intense (e.g. Marengo et al. 2010) with potentially stronger negative impacts on crop yields (e.g. Oliviera et al. 2013; Rosenzweig et al. 2014).

Chapter 5: The process of translating qualitative scenario assumptions into quantitative model input and associated uncertainties

1. Introduction

The objectives of the Carbiocial scenario-building process were manifold and reflect the problem setting (see Box 1), the needs of stakeholders, and the internal process of knowledge aggregation within the research group. Due to the scope of the project on regional carbon management by land use, also the focus of the scenarios is in aspects strongly related to this issue. The main intention of the scenarios was to provide an instrument for informed stakeholder dialogues and as a framework for identifying potential environmental risks associated with specific regional development trajectories. First, communicative bridges between and among social and natural sciences had to be constructed by using methodologies that would serve the needs of all involved. The social scientists insisted on the actor's perspective on current and future developments and on the integration of local data; the natural scientists needed to find a meaningful pattern to orient the multiple disciplinary research approaches and translate them to the simulation models within Carbiocial. We chose a blend of all economic, biophysical, and social factors that were needed as input for the different models involved as a guiding principle for all scenarios and the development of storylines. These guiding principles helped to establish common ground for communicating between and among the different disciplines.

In this context one essential application was the development of qualitative scenarios, also known as storylines. Storylines describe different future development pathways of Southern Amazonia (explorative scenarios) in the form of narratives. Qualitative scenarios in the form of narratives have the advantage of being able to express the points of view of different stakeholders and stakeholder groups as well as experts simultaneously (Alcamo et al. 2008). Furthermore, they qualify as a means of constructing said communicative bridges between social and natural scientists as well as scientists in general and stakeholders. By this it was possible to integrate stakeholder and stakeholder groups into the process of scenario construction and consequently benefit from their extensive and detailed knowledge about current land-use dynamics and practices as well as their understanding of potential future developments in the region.

Another essential application was the development of quantitative scenarios, made up of quantitative analysis and visualization of past and future land-use change (e.g. deforestation, agricultural intensification), which is known to heavily impact greenhouse gas emissions as well as biodiversity (Chaplin-Kramer et al. 2015). Quantitative scenarios were necessary to express qualitative assumptions in more formal and transparent terms in order to create common ground for discussions on how different futures might unfold in a scientific or expert setting. Moreover, quantitative data were needed as input for the different models involved in simulating future land-use change dynamics and corresponding impacts on the environment as well as socio-economic structures.

The Carbiocial approach of generating combined qualitative and quantitative scenarios has been used in many studies. For instance, on the global scale, Cosgrove and Rijsberman (2000) describe the process of developing scenarios in order to depict the world water situation in 2025. Nakiconevic (2000) reports on the SRES scenarios with a focus on global greenhouse gas emissions up to 2100 developed following specific recommendations made by Alcamo et al. (1995). Alcamo et al. (2005) describe the process of developing the Millennium Ecosystem Assessment scenarios with a focus on evaluating the potential development paths for ecosystems and their services up to 2050 (Carpenter et al. 2005). Here the scenario development process is of special interest as it put equal emphasis on qualitative and quantitative scenarios as well as putting special emphasis on a participatory approach to scenario construction. Another important example is the Global Environmental Outlook scenarios with their fifth installment (UNEP 2012). These scenarios go one step further by describing main developments of the environment on a global scale as well as on a regional scale by providing complementary world regional scenarios up to 2050. Further examples of generating combined qualitative and quantitative scenarios are the OECD Environmental Outlook up to 2030 (OECD 2008) or the World Agriculture: Towards 2030/2050 scenario (Alexandros et al. 2012). This list could go on (especially by including regional and local scenarios) which only accentuates the acceptance and implementation of the approach of generating combined qualitative and quantitative scenarios in the scientific community.

Study area
Mato Grosso (MT) has an area of 907,000 km² and a population of 3.2 million people (IBGE 2013). 69,807 km² of land is used for soybean cultivation (IBGE 2015) and 1,149 km² was deforested in 2013, which constitutes an increase of 52% in comparison to 2012 (INPE 2013). Another dominant land-use sector is cattle ranching, with a total herd size of 28.4 million animals (IBGE 2015). Here, the expansion of area used for soybean cultivation and cattle ranching could be identified as the primary cause of conversion of natural ecosystems to agricultural land (Greenpeace-Brazil 2009; Barona et al. 2010).
Pará (PA) has an area of 1.25 million km² and a population of 8 million people (IBGE 2013). Only 11,969 km² of the land is used for soybean cultivation (IBGE 2015). In 2013, 2,379 km² was deforested, which shows an increase of 37% in comparison to 2012 (INPE 2013). The dominant land-use sector is cattle ranching, with a total herd size of 19.2 million animals (IBGE 2015). A hotspot of LULCC is along the Cuiabá-Santarem highway (BR-163), the most recent of the “development highways” used to acquire the agriculturally underdeveloped northern parts of Brazil for crop cultivation and cattle ranching (Coy and Klingler 2008).

The approach further referred to as Story and Simulation (SAS) approach (Alcamo et al. 2008), has following advantages. It helps to produce scenarios that are relevant to stakeholders and experts. This is achieved due to the iterative procedure that is employed to generate the scenarios. The constant feedback loops between interest groups ensures that the final scenarios incorporate knowledge that is of relevance to policy makers, scientists, planners as well as practitioners. In addition, the active involvement of all relevant interest groups supports generating legitimate scenarios. Moreover, the produced knowledge can be conveniently communicated to all interest groups. Scientists and planners might be more interested in hard numbers while practitioners might profit from storylines due to them being understandable and captivating. Scenarios built following the SAS approach include numerical data generated by computer models which are mostly transparent and can be scientifically reproduced while providing the basis for checking the consistency of qualitative scenarios. Therefore, scenarios produced by applying the SAS procedure are credible. Finally, the incorporation of different mindsets (practitioners might think in different terms and temporal dimensions than policy makers or planners) in the process of scenario building can be a source of creativity.

But a key issue in developing combined qualitative-quantitative scenarios is their consistency. Qualitative scenarios developed by stakeholders will not necessarily be consistent with those developed by using models. The main challenge here is to translate qualitative, stakeholder-generated scenarios (storylines) into suitable model inputs that can be used to generate quantitative scenarios. With this challenge in mind, the objectives of this chapter are to:

- Describe the process by which qualitative information is translated into quantitative information in the Carbiocal scenarios
- Analyze the effectiveness of this process, especially by identifying the uncertainties that arise in the translation process
- Suggest ways to improve the translation process

2. Qualitative Scenarios

2.1. The applied process of developing storylines

It was decided that the aggregation of qualitative data alongside the logic of the previously enumerated input data would provide the necessary interface to the models; to limit bias and to include decades of qualitative research in Amazônia, all available Amazonian experts in Germany were invited to support the CarBioCial-team in its effort to supply content to the four storylines in a day-long and quite controversial brainstorming session. During the process of storyline development the participating social science colleagues were provided a list of all drivers and were asked for their opinion as to how these aspects would unfold within the respective scenarios. As a result each storyline now included respective verbal descriptions that could serve as a starting point for the quantification process. It became clear that multiple trajectories for different Amazonian sub-regions are imaginable and that the situation at the BR-163, alongside the soy export corridor are quite specific. The rigid orientation towards the input factors of the models in place, namely, population, agrarian production, livestock, agrarian and environmental policies, protected areas, infrastructure and impact of climate change helped to organize the abundant knowledge towards workable and compatible data.

The main results of this process were four storylines that depict plausible development pathways for the study region until 2030, with one being the baseline scenario. The respective narratives were drafted by the CarBioCial project team members based on the discussions of the expert meeting. Afterwards the results were translated into Portuguese, the storylines were discussed with about 30 representatives of governmental and non-governmental institutions in Brasília, MT and PA to assess their plausibility, and modified accordingly. The depth of the respective debates varied according to the time budget of the institutional representatives. To complement the voice of missing local stakeholders, discussions during field days and data from qualitative and biographical interviews that referred to future perspectives were integrated.

2.2. The resulting storylines

The “Trend” storyline is used as a reference for future land use change. It is based on a forward projection of growing demand for agrarian products, a continuation of the conversion of natural ecosystems, the technical and social consolidation of Highway-163 and local populations, as well as the further intensification of agrarian production and sporadic law enforcement.

Storyline I describes a scenario of “Legal Intensification”. It assumes a growing demand for agrarian products, but with effective law enforcement preventing the illegal conversion of natural ecosystems; the technical and social consolidation of Highway-163 and its populations will include a high intensification of agrarian production with regard to increased production as well as productivity; law enforcement of social and environmental law will be effective under conditions of continuing climate change.

Storyline II describes a scenario that is characterized by “Illegal Intensification”. As with Storyline I it assumes a growing demand for agrarian products, but with only very sporadic law enforcement which will lead to the further conversion of natural ecosystems; the technical and social consolidation of Highway-163 and its population will include a high intensification of agrarian production, specifically increased production.

Storyline III describes a “Sustainability” scenario which is the most complex, since it projects a completely new local, national and global society within possible legal and societal parameters. The society in Southern Amazonia will enjoy a social model where participation, citizenship and the enforcement of existing laws are complemented by further adequate laws, the protection of resources with participatory monitoring. The political will to initiate local, inclusive and sustainable development in favor of the majority of the population is assumed. Moreover, available knowledge and technical resources are utilized to satisfy a growing national and global demand for certified agrarian goods. Also a clarification of land rights in the project region is expected.

3. Quantitative Scenarios

3.1. The process of developing the quantitative scenarios

A set of land-use drivers was identified to quantitatively describe the evolution of key factors until 2030. These key variables were derived from the analysis of deforestation drivers by Lambin and Geist in (2003) (also see De Espindola et al. 2012) but were already oriented toward the input data requirements of the land-use change model that was applied to the development of land-use scenarios (see Section 2.1). They include quantitative information on population development, crop production, livestock numbers and crop yield increases due to technological change, as well as assumptions about the conversion of natural ecosystems, infrastructural development related to highway BR-163, protected areas, and the degree of law enforcement. The translation process was expert-driven and less formal than, for example, the fuzzy cognitive maps approach described by Jetter and Kok (2014) (also see van der Sluis et al. 2015) or the methods discussed by Alcamo et al. (2008). Land-use drivers were subdivided into three topics: population change, agricultural development and land-use policy.

In the first step statements from each storyline regarding these topics were extracted and interpreted in light of their potential meaning for the land-use change modelling process. In the second step this qualitative information was translated either into numerical data describing the trends of population development, agricultural production and productivity changes (e.g. crop yield increases) or, in case of land-use policy, into rules that were integrated into the land-use change models. This process was supported by communication within the Carbiocial-team, including communication with the respective Brazilian partners of the sub-projects.

3.2. The applied land-use change model

Land-use and land-cover change (LULCC) were simulated with the spatially explicit LandSHIFT model. The model is fully described in Schaldach et al. (2011) and has been tested in different case studies for Brazil (Lapola et al., 2011; Lapola et al., 2010). It is based on the concept of land-use systems (Turner et al., 2007) and couples components (in the form of sub-modules) that represent the respective anthropogenic and environmental sub-systems. Land-use change is simulated on a raster with the spatial resolution of 900m x 900m that covers the territories of the federal states of MT and PA. LandSHIFT simulates the spatiotemporal dynamics of settlement, cropland and pasture by regionalizing their state-level drivers to the raster level in 5-year time periods. These drivers include human population, livestock numbers, crop production, and crop yield increases due to technological change. Input on cell-level comprises the state variables “land-use type” and “human population density”, as well as a set of parameters that describe its landscape characteristics (e.g. terrain slope), road infrastructure, and zoning regulations.

3.3. Input data requirements of the applied land-use change model

As mentioned above (see Section 3.1), land-use drivers were classified into three categories: human population, agricultural development, and land-use policy. The subdivision of land-use drivers is oriented toward the data input requirements of the land-use change model. The sub-module responsible for the calculation of urban expansion requires information on expected population growth per federal state. The sub-module responsible for the calculation of cropland expansion requires information on assumed agricultural production changes as well as spatialized crop yield information per grid-cell as calculated by LPJmL (Bondeau et al. 2007). Furthermore, information on potential crop yield changes due to technological progress is required. The sub-module responsible for the calculation of pasture expansion requires information on assumed changes of livestock numbers and current spatialized net primary productivity (NPP) on grassland cells. Land-use policy information is required to serve as rule or constraint for the allocation of cropland or pastures and the resultant expansion of agricultural productive land and consequent conversion of natural habitats.

3.4. Consistency between storylines and quantitative model input

In order to run the land-use change model, the qualitative storyline assumptions had to be translated into numerical model input. Naturally, not all of the model inputs could be derived directly from storyline assumptions. The other way around not all storylines assumptions were qualified to be translated directly into quantitative model input. In regard to demographic data, only the general trend of population development in Southern Amazonia until 2030 could be directly derived from the storylines. Here it was not differentiated between urban and rural population. Accordingly, an urbanization trend could not be deviated from storyline assumptions.

Concerning agricultural model input, the general crop production trend and the trend in livestock numbers in Southern Amazonia until the year 2030 could be deduced directly from storyline assumptions. Moreover, changes regarding the production of specific crops that arise from a changing global consumption pattern could be translated from the storylines. The development of crop yield efficiency could be deduced for one specific scenario. The Sustainability scenario describes a world that is characterized by the substitution of meat consumption by crop products. Accordingly, it assumes a concentration of research efforts on the increase of crop yield efficiency, and thus implies an increase of 30% above the trend of crop yield efficiency enhancement until 2030 as taken from a global scenario analysis with the economic trade model IMPACT (Rosegrant 2013) conducted in the context of food security research (Chaudhury et al. 2013).

Most of the data concerning future land-use policy could be translated directly from storyline assumptions. The level of road infrastructure development was considered to be a steady state value and equal for all four scenarios as it was common ground that all scenarios should portray the development situation around the newly established highway BR-163. The level of law enforcement was an important element of the storyline considerations and is one of the elements that help to distinguish the scenarios from one another. It also strongly influences simulated expansion of agricultural land within the land-use change model and was derived directly from the storylines and integrated in form of a constraint for agricultural expansion. The same was done for policies that prohibit or allow the conversion of specific types of land-cover. The possible change of extent and location of conservation areas in Southern Amazonia was not a specific element of the storylines. Summarizing, except for the trend of a possibly occurring urbanization, the trend of yield efficiency increases (except for the *Sustainability Scenario*), and the possibly occurring dynamics of conservation areas all needed model input could be directly derived from storyline assumptions. Hence, consistency between storylines and quantitative model input could be mostly maintained.

Table 5-1: basis for model input

model input (categories)	**From storylines**	**Not from storylines**
Demographic characteristics	population trend (aggregating rural and urban population) in Southern Amazonia to 2030	
		urbanization trend in Southern Amazonia to 2030
Agricultural characteristics	general crop production trend in Southern Amazonia to 2030	
	livestock number trend in Southern Amazonia to 2030	
	changes of agricultural production pattern due to changes in consumption pattern	
	trend in yield efficiency increase in Southern Amazonia to 2030 (*Sustainable Development Scenario*)	
		trend of yield efficiency increase in Southern Amazonia to 2030 (all except *Sustainable Development Scenario*)
land-use policy	level of road infrastructure development in Southern Amazonia	
	law enforcement in regard to land-use policies in Southern Amazonia	
	land-cover type allowed for conversion to agricultural land	
		dynamics (extent and location) of conservation areas in Southern Amazonia

4. The process of translating qualitative into quantitative scenarios

4.1. General assumptions

The storylines for the *Trend Scenario,* both *Intensification Scenarios*, and the *Sustainability Scenario* set the spatial reference for quantitative scenarios to two federal states in Brazil. PA, the northern of both federal states, still undergoes a process of agricultural allotment (e.g. Laurance et al. 2014) while the southern of the states, MT, is agriculturally consolidated and experiences a process that leads away from agricultural expansion towards the intensification of existing agricultural land (e.g. VanWey et al. 2013; Spera et al. 2014; Cohn et al. 2014). The so called agricultural pioneer frontier, an area of rapid land reclamation and infrastructure development (Foweraker 2002), runs approximately along the border separating both states. To the south of the agricultural development frontier, large land holders and corporate groups specializing in the production of cash crops for international export buy land from cattle farmers and smallholders that was formerly utilized as pasture or grazing land. In the region to the north of the agricultural development frontier, land reclamation is in the hands of land-less and small holders that see their chance for an economic and social ascension in acquiring small parcels of land in order to cultivate it mostly through shifting cultivation, producing crops preferably for subsistence reasons (e.g. Soler et al. 2014) (also see Box 1). This information sets the spatial frame for quantifying the qualitative assumptions made in the storylines. The time frame for the scenario exercise was set to cover the years from 2010 to 2030.

Furthermore, it was originally planned to integrate two climate change scenarios through dynamically adapting crop yields according to changing precipitation amounts and patterns. These adapted crop yields were not provided by the responsible sub-project due to timely constraints. Therefore, climate change could not be incorporated into the quantitative scenarios.

To summarize, the translation of general assumptions made within the qualitative storylines to numerical model input/rules had the following uncertainties:

a. Uncertainty is introduced by not implementing changing cultivation patterns and crop yields due to climate change.

b. The setting of the time frame to 2010-2030 leads to the emergence of uncertainties in regard to not considering strong impacts that were expected to occur after 2030. Stakeholders (practitioners, planning authorities, and policy makers) as well as experts expected climate and economic shocks with a significant impact on land-use in the region to occur mainly after 2030.

The following are options to reduce these uncertainties:

- The time plan of some sub-projects could have been improved in order to allow for all relevant information to be available in order to be integrated into the quantitative scenarios.
- The time frame of the scenarios could have been extended to 2050 in order to integrate shocks and surprising developments.
- Surprising elements could have been integrated before 2030 in order to compensate for the relatively short time frame of the scenarios.
- In general, the acceptance of scenarios could be improved by increasing stakeholder integration in the process of qualitative scenario construction (i.e. interactive scenarios) or by establishing an iterative feedback loop between experts and stakeholders in the process of scenario quantification.

4.2. Demographic characteristics

Under the *Trend*, *Illegal Intensification* and *Legal Intensification* scenarios, human population changes until 2030 were calculated in line with the observed trend from 1973-2000. Trend extrapolation was calculated with the least squares method (Rao et al. 1999). We will exemplarily discuss the translation of one storyline assumption: “population dynamics and growth continue according to agricultural pioneer frontier dynamics” in order to shed light on some underlying decisions, and thus add to the transparency of the translation process.

To translate this assumption from the storylines, the following was done:

a. Data on past population growth had to be on a spatial resolution of at least federal state level in order to be applicable directly (without further disaggregation) as a basis for the extrapolation of past trends on the federal state level. Therefore, data on past observed population growth was taken from the IBGE database (IBGE 2013) with a spatial resolution on the municipality level for the period from the year 1973 to the year 2000 and aggregated (summed up) to the federal state level.

b. Data from the FAO database for instance was only available on the country level. This data would have consequently to be disaggregated to the federal state level which would have increased uncertainty in regard to the final modeling results (land-use maps). A trend function was fitted to the observed past population development (reference period 1973-2000) per federal state and extrapolated until the year 2030.

In PA this results in a population increase from 6.9 million people in 2010 to 9.3 million people in 2030 while in MT we find an increase from 2.7 million to 3.7 million people during that period.

In contrast, the storyline of the *Sustainability Scenario* assumes that population growth in MT and PA slows, mainly due to lower in-migration from other parts of Brazil. This slowdown is more intense in MT. In the case of PA the assumed slowdown also present but is extenuated by job opportunities created due to the pioneer dynamics of the agricultural frontier and the construction hydroelectric dams. The population growth rate was adjusted by -10% for MT and -5% for PA for every five year modeling step. The numbers for both scenarios are shown in Table 5-2.

Table 5-2: translation table: demographic characteristics

model input (categories)	Storylines	model assumptions
population development	population dynamics and growth continue according to agricultural pioneer frontier dynamics (storylines Trend, Legal Intensification, Illegal Intensification)	trend projection (method of the least squares) until 2030
	population growth stabilizing; less migration of land-less from other Brazilian regions (storyline Sustainable Development)	trend projections (method of the least squares) until 2030 – growth rate correction (MT: -10%; PA: -5%) per time-step

To summarize, the translation of demographic characteristics from qualitative storylines to numerical model input/rules had the following uncertainties:

a. The trend projection of state-wide population growth does not necessarily reflect migration dynamics along the agricultural pioneer frontier.

b. Uncertainty emerges as we assume that population growth is stabilizing as a result of less work opportunities along the BR-163; it could also be assumed that a general betterment of livelihoods in the study area (as is integral part of storyline Sustainable Development) might in turn cause an increase of migration into the region.

c. Socio-economic behavior of agents is not represented in a logical way. For instance, the intensive infrastructure development along the BR-163 could initiate a process that leads to less intensive frontier dynamics (i.e. land-less and smallholders could settle down instead of selling their land to cattle ranchers and continue to move northwards).

The following are options to reduce these uncertainties,

- Population growth could have been adapted on a regional basis within both federal states in a way that migration into frontier regions could have been quantified to be above the country-wide population growth dynamics.

- Surprising events could have been integrated into the qualitative and quantitative scenarios. In-migration, and thus population growth could have been slowed due to, for instance, declining world market prices for specific cash crops or meat products. Also the in-migration of farmers and land-less could increase due to new emerging national and/or international markets or an implementation of land tenure rights especially in PA.

- It is necessary to incorporate more detail about the driving forces of land-use change. For instance, infrastructure development (e.g. roads, public institutions) in settlement areas could slow pioneer frontier migration dynamics.

4.3. Agricultural characteristics

The assumptions regarding the development of agricultural production as well as yield efficiency increases due to technological change in the four scenarios are summarized in Table 5-3.

Table 5-3: translation table: agricultural characteristics

model input (categories)	Storylines	model assumptions
agricultural production	agricultural production is expanding and intensifying (storyline Trend)	trend projection (method of the least squares) until 2030
	agricultural production is expanding and intensifying further accelerated due to demand from Asian countries (storyline Legal Intensification and Illegal Intensification)	trend projections (method of the least squares) until 2030 + additional growth according to population growth in Asian countries
	agricultural production specializing on fresh products (niche market); the better the development of trade structures, the stronger smallholder and medium business production (storyline Sustainable Development)	trend projections (method of the least squares) until 2030 + additional production growth (pulses, fruits, vegetables, soy); production correction of soybean (exported fraction) due to less export demand
	high intensification regarding crop production due to research concentrating on crop yields efficiency (storyline Sustainable Development)	crop yield efficiency development adapted by an additional +30% over 20 years (2010-2030)
livestock production	livestock numbers continue to rise (storyline Trend)	trend projections (method of the least squares) until 2030
	livestock numbers continue to rise further accelerated due to demand from Asian countries (storyline Legal Intensification and Illegal Intensification)	trend projections (method of the least squares) until 2030 + additional growth according to population growth in Asian countries
	increases of livestock production are realized through intensification rather than expansion of productive land to an increasing extent (storyline Legal Intensification and Illegal Intensification)	net primary productivity of pasture cells is successively increased until 2030 (MT: +9% per time step, max: +50%; PA: +4.5% per time step, max: +30%)
	agricultural production specializing on fresh products (niche market); worldwide trend toward healthy and sustainable diet (storyline Sustainable Development)	trend projections (method of the least squares) until 2030 -70% livestock numbers due to healthy and sustainable diet

In the *Trend Scenario* the international and national demand for agricultural goods and commodities increases in line with previous trends (1973-2000). Consequently the estimates for future crop production, livestock numbers and human population are derived by statistically extrapolating the respective census data, again using the least squares method. Information on crop yield efficiency increases until 2030 due to technological advances (e.g. plant breeding, improved agricultural management methods) are derived from a global scenario analysis as mentioned above (see section 3.4) and have been adapted (increased) by an additional 30% until 2030 in the case of the *Sustainability Scenario*.

The *Legal Intensification*- and the *Illegal Intensification Scenario* assume that future agricultural production shows an even stronger increase than the historic trend, mainly driven by growing demand from Asian countries, which are expected to experience rapid population growth in combination with increasing per capita income (Kalimili and Fantom 2016). The Asian market resembles the most important export market for commodities produced in Brazil with close to 25% of the total Brazilian exports. Other important export destinations are the European Union (18.7%) and the United States of America (12.1%) as well as Argentina (6.3%) (WTO 2016). The additional increase in agricultural production is related to estimates of future population growth in the four most important export countries for agrarian products from Brazil in Asia: China, Thailand, Japan and South Korea. Focusing on these countries, China is the largest market, with a share of 88.6% while Thailand accounts for 6.2% of the market share, Japan for 2.7% and South Korea for 2.1%. The weighted cumulative change rates of population growth in the selected Asian countries were multiplied with the increased rates of agricultural production in MT and PA. This resulted in an adapted production growth rate that accounted for increasing agricultural production as well as the export-induced production increases generated by a growing population in Brazil’s main Asian export destinations. To give an example: If the population growth rate in China is 10% above the production growth rate in MT or PA, an additional increase of agricultural production in the Brazilian federal states of 8.6% (10%*88.6%) is assumed. Crop yield increases are similar to those in the *Trend Scenario*. Additionally, both intensification scenarios presume the intensification of cattle ranching. In PA, we assume an intensification rate of 4.5% per time step up to a maximum of 30%. That means that the biomass productivity of any pasture cell is increased by 4.5% until biomass productivity is 30% higher than in the base year. As agriculture in MT is assumed to be more mechanized, large scale, and world market oriented (Jasinski et al. 2005; Arvor et al. 2012), we apply an intensification rate of 9% up to a maximum value of 50%. These assumptions are based on observed pasture intensification rates in Brazil. According to Wint et al. (2007) and Lapola et al. (2014), the stocking density of pastures in Brazil rose continuously from 1990 to 2010, with a total increase of 45% during that period. The two scenarios differ in respect of the assumed enforcement of environmental law.

The central aspect of the *Sustainability Scenario* that affects agricultural production is a general shift to a more vegetarian-oriented diet based on the recommendations from the World Health Organization (WHO) (e.g. Srinivasan et al. 2006; Amine et al. 2002). To estimate future reduction potentials of meat consumption we compared current meat consumption with the recommended amounts of meat consumption following the recommendations of the Harvard Medical School for Public Health (Stehfest et al. 2009) (Table 5-4).

Table 5-4: quantities of commodities replacing animal product consumption

commodity	Ratio kcal/g[1]	Share of meat substitution	additional requirement per capita/d		additional requirement t/y	
			kcal	g	MT	PA
soybean	1.8	60%	318	177	196,084	489,773
pulses	3.37	27%	143	43	47,636	118,984
fruits	0.4	6.5%	34.5	92.5	102,473	255,955
vegetables	0.25	6.5%	34.5	148	163,957	409,528

Source: own calculations

The Harvard Medical School for Public Health recommends 10g beef, 10g pork and 46.6g of chicken and eggs per day, which is a total of 66g/d animal products (Stehfest et al. 2009). Consequently the average yearly intake of meat should not exceed 22.3kg per person. Comparing the recommended to the average meat consumption in Brazil, a mean reduction potential of calorie intake from animal products of 156g/day per person was estimated (-70%). Based on these findings we assume that meat production in the two states decreases by 70%. At the same time, we assume a reduction in the share of soy exported by 10% (70%-60% (see below)) due to decreased international fodder exports coupled with increased soy exports due to worldwide substitution for meat consumption. We model the process of dietary transition as a gradual process occurring over a 20-year period (2010-2030). The emerging nutritional gap resulting from a reduction of meat consumption of 530kcal/day per person (in light of the WHO recommendation per person of ~2512 kcal/day) needs to be substituted with calories from other sources. Following the approach of Stehfest (2009), soy protein fills 60% of missing calories. According to the recommendations of the World Cancer Research Fund, fruits and vegetables should account for 13% of the replacement, with the remaining share made up of pulses (see Table 5-4).

Finally we adjusted agricultural production taking into account the decrease in population growth described in the Sustainable Development storyline. Accordingly, the growth rate of agricultural production for domestic markets, amounting to 57.5% of the total agricultural production (MAPA, 2012), was reduced by -10% (MT) and -5% (PA) respectively, compared to the *Trend Scenario*. As assumed in the storyline, crop yields increase faster in the Sustainable

[1] FOASTAT: *Food Balance Sheet. Brazil.* http://faostat.fao.org/site/609/default.aspx#ancon

Development storyline than in the other scenarios. An additional 7.5% crop biomass per hectare was assumed to be realized for each time step.

To summarize, the translation of agricultural characteristics from qualitative storylines to numerical model input/rules had the following uncertainties:

a. A growing Asian population might not be the only decisive element of an increased livestock/feedstock production in the study region. Uncertainty emerges due to not integrating per capita income growth, and thus increasing meat consumption in Asian countries (Pingali 2007; Zhai et al. 2013).

b. Recent trends of agricultural expansion in Brazil show that agricultural production increases are realized by agricultural intensification to an increasing extent (Cohn et al. 2014; Grafton et al. 2015). Uncertainty is introduced by not dynamically adjusting the proportion of crop production increases that are realized via intensification on existing agricultural land (storylines Trend, Legal Intensification, Illegal Intensification).

c. There are several biophysical barriers to agricultural expansion that were not considered in the scenarios, and thus lead to uncertainties. For instance, the northern region of PA along the BR-163 is rather hilly (Farr and Kobrick 2000), and thus characterized by high slopes. These characteristics impede or prevent mechanized, large-scale agriculture, and thus make this region less attractive for farmers specializing on the production of cash crops as has been brought forth by several stakeholders.

d. Uncertainties are introduced by not taking into consideration that there is a biological maximum to the net primary productivity of pasture cells under certain conditions (soil conditions, type of forage plant).

e. The degradation of agricultural land was not considered in the quantification of the qualitative scenario assumptions but plays an important role in the context of land-use and land-use change in the study region (e.g. Hohnwald et al. 2016).

The following are options to reduce these uncertainties,

- Driving forces of agricultural development could have been quantified in a more detailed fashion. For instance, the mentioned per capita income growth in most Asian countries could have been integrated into the quantitative scenarios. The credibility of the scenarios could be improved considerably by increasing the degree of detail (e.g. Alcamo et al. 2008).

- The establishment of new agricultural land could be halted at specific geographical locations due to their ineptitude for mechanized, large-scale agriculture (cash crops).

- Also, the integration of degradation of agricultural land would have led to significantly different patterns of agricultural expansion/contraction. Unfortunately, degradation of land resources was only assessed on the basis of simulated land-use scenarios and not as influential driver of land-use change in the scenarios.

- The increasing trend toward agricultural intensification could have been implemented by dynamically adjusting the proportion of agricultural production increases realized by agricultural intensification.

- Oversimplification of some elements leads to uncertain simulation results and need to be considered in a less simplified fashion (i.e. biological maximum to net primary productivity on pastures due to bio-physical conditions).

4.4. Land-use policy

As pointed out earlier, land-use policy was integrated into the applied land-use change model either as a constraint against land-conversion in designated areas (e.g. nature protection) or as a factor prohibiting (or not prohibiting) the conversion of a specific land-use type (e.g. forest). Road infrastructure typically influences the attractiveness of a cell for urbanization or agricultural development. Storyline assumptions and their translation into numerical model input/rules are summarized in Table 5-5.

Table 5-5: translation table: land-use policy

model input (categories)	Storylines	model assumptions
land-use policy	conversion of natural ecosystems is taking place (storyline Trend, Illegal Intensification)	transition probability forest: 50% (due to cost of conversion) transition probability Cerrado: 70% (due to cost of conversion)
	effective law enforcement; conversion of forest according to Brazilian Forest Code (storyline Legal Intensification)	transition probability forest: 50% (due to cost of conversion) transition probability Cerrado: 70% (due to cost of conversion); all newly established agricultural land-use on former forest cells as mosaic land-use type (*Mosaic "Legal Reserve"*) 20% cropland or pasture/80% rainforests
	conversion of areas defined as Cerrado less likely to happen; Soy-Moratorium continues after 2016; Cattle-Moratorium continues after 2019 (storyline Sustainable Development)	transition probability forest: 0% transition probability Cerrado: 30%;
	no illegal transformation of natural land cover; effective law enforcement (storyline Legal Intensification, Sustainable Development)	no land-use within protected areas (exception: land use according to base-map (2000))
	law enforcement in place but rather inefficient due to resource deficiency (storyline Trend)	no land use within protected areas (exception: land use according to base-map (2000))
	ecological protected areas are used for illegal agricultural expansion; sporadic law enforcement (storyline Illegal Intensification)	no land use within protected areas (military, indigenous); land use/land use change allowed in ecological protected areas
road infrastructure development	infrastructural development continues as planned: BR-163 paved (all storylines)	BR-163 is integrated into database road-map layer as paved road

In the *Trend Scenario*, natural land-cover that is not protected can be converted into agricultural land and settlement area. Moreover the improvement of the BR-163 increases the likelihood that cells near this road are transformed into agricultural land. These assumptions are also valid for the *Legal Intensification Scenario*, but natural land-cover that is converted between 2010 and 2030 is, in contrast, only partly used for agriculture. According to the new Brazilian forest code, 80% of each cell will have to remain forest (Soares-Filho et al. 2014). These areas were classified as Mosaic land-use type. The policy settings for the *Illegal Intensification Scenario* weaken the protection status of natural land-cover within designated areas. While the conversion of natural ecosystems within indigenous and military areas is still prohibited, the conversion of forest and Cerrado within other types of protected areas (environmental protection status) is allowed. The most rigorous protection natural land-cover is assumed in the *Sustainable Development Scenario*. In addition to natural land-cover within protected areas, also forest outside of these areas is fully protected and cannot be converted into agriculture between 2010 and 2030 due to the Soy- as well as Cattle Moratorium (Nepstad et al. 2014; Gibbs et al. 2015; Gibbs et al. 2016).

To summarize, the translation of land-use policies from qualitative scenario assumptions into numerical model input/rules had the following uncertainties:

a. Conservation areas are considered to be steady state from 2010 to 2030. Uncertainties emerge as conservation areas might expand or contract according to newly introduced development initiatives or land-use policies (e.g. Pressey et al. 2007).

b. Uncertainties are introduced by setting transition probabilities of natural habitats to reflect expected economic behavior alone (storylines Trend, Legal Intensification, Illegal Intensification). Other factors (i.e. land tenure, land speculation) also play a role in regard to the probability of conversion of certain land-cover types.

c. The assumption of a paved BR-163 for all scenarios adds to uncertainties as other viable options are not considered in at least one of the scenarios.

d. The pavement of the BR-163 is not completed until today (2016). We assume the whole length of the BR-163 (1.780 km) paved from 2010 to 2030 which adds to uncertainties as the accessibility of regions plays an important role in regard to land-use change in the study area (e.g. Peres 2001; Soares-Filho et al. 2006).

e. Some transition probabilities are set according to policies that are in effect. For instance, in the *Sustainable Development Scenario* the conversion of forest to pasture or cropland is prohibited due to the Soy- and Cattle Moratorium (see Nepstad et al. 2014; Gibbs et al. 2015; Gibbs et al. 2016). Due to the nature of the political process, policies are prone to change regularly, especially in Brazil a constant insecurity in the anticipation of new laws and norms to come prevails (Campbell 2011; Campbell 2014).

The following are options to reduce these uncertainties,

- An expansion or contraction of conservation areas would have needed to be integrated dynamically in order to reflect changing land-use policy. That could have been accomplished by incorporating feedback from planning authorities.

- More research in regard to the determining factors of a conversion of natural habitats, especially in PA (i.e. land tenure, land speculation), would have led to more certain results concerning LULCC modeling.

- Other viable transportation options could have been considered in at least one scenario. It was discussed to integrate the construction of a railroad line from MT to PA in the *Sustainable Development Scenario* in order to reflect the tendency toward less environmentally damaging transport alternatives for agricultural commodities to their respective export harbors. Due to resource constraints, this could not be accomplished.

- The current status of the pavement of the BR-163 could have been considered. Moreover, the pavement of the BR-163 could have been incorporated in a dynamic fashion over the whole simulation period.

- Surprises or non-linearity could have been incorporated in the qualitative and quantitative scenarios. This measure could have helped to reflect the volatile policy process in Brazil.

5. Discussion

5.1. Sources of uncertainties

Uncertainties can be categorized according to the system they relate to. Therefore, we will classify the multitude of possible uncertainties corresponding to the Carbiocial scenario development process into the categories social, economic, political, and bio-physical uncertainties.

Social uncertainties result from simplification of assumptions or not-consideration of social factors that do have an influence on scenario results. For instance, we assume that the extrapolation of state-wide observed population dynamics also reflects population dynamics along the agricultural pioneer frontier. Realistically, population growth along the pioneer frontier will be accelerated in comparison to other regions within the federal state due to increased in-migration of land-less and smallholders seeking land and work opportunities (e.g.

Caviglia-Harris 2013). In our case, simulated land-use change dynamics around the BR-163 were perceived as too weak by stakeholders while land-use change in other parts of the study region was criticized to be too intensive. A subdivision of the federal state into smaller regions (e.g. agricultural pioneer frontier/non-frontier) combined with a quantification of population growth separately for every sub-region could have increased acceptability of the scenarios by stakeholders. Moreover, the scenario assumption of population growth slowing and finally stagnating in the case of the *Sustainable Development Scenario* was regarded as uncertain. On the one hand, especially in regard to this scenario, we could have assumed that population growth could have accelerated at a certain point in time due to improving livelihood conditions. On the other hand, this might only have occurred after several decades which is not within the temporal scope of the scenarios. Additionally, the socio-economic behavior of agents is not represented in a realistic way. Intensive infrastructure improvements along the BR-163 could cause smallholders to settle down instead of continuing their constant move northward (Coy and Klingler 2008). This would, over time, slow down agricultural pioneer frontier dynamics.

Economic uncertainties result from simplification of assumptions or not-consideration of economic factors that do have an influence on scenario results. We consider agricultural production in the case of both *Intensification Scenarios* increased due to population growth in Asian countries, one of the main export destinations of agricultural commodities produced in Brazil (WTO 2016). We do not consider the observable growth of per capita income in these countries which would lead to a shift in consumption patterns (Pingali 2007; Zhai et al. 2014). An increasing consumption of meat products will lead to increasing livestock numbers and an increased production of fodder crops above the assumed trends. Further, we do not consider shifting proportions of expansion and intensification of agricultural land. Several authors (e.g. Cohn et al. 2014; Grafton et al. 2015; Gollnow and Lakes 2015) point out that recent agricultural production increases have been realized through agricultural intensification to an increasing extent. This is not considered in the Trend Scenario for crop as well as livestock production and only partially considered within both *Intensification Scenarios* (livestock production) and in the *Sustainable Development Scenario* (crop production). Also, the transition probabilities of natural vegetation in all scenarios are set according to economic considerations or land-use policy constraints (Cattle- and Soy Moratorium) alone. Other factors, like the land tenure situation or land speculation in specific regions, will also have a decisive influence on the transition probability of specific land-cover types (e.g. Robinson et al. 2014). This has not been considered in the scenarios.

Political uncertainties emerge due to simplification of policy assumptions. First of all, we consider conservation areas to be steady-state throughout the whole scenario simulation period (2010-2030). This is a strongly simplified assumption considering a volatile policy process in Brazil (Campbell 2011; Campbell 2014). Conservation areas are rather susceptible to expand or contract according to decisions made by the dominant political party. And even within one legislative period, new laws and norms in regard to land-use and nature conservation are introduced on a regular basis in Brazil (Campbell 2011). The transition probabilities of forest land-cover types are set according to implemented land-use policies. The Soy Moratorium prohibits major soybean traders to buy soy produced on former forest land that was converted after 2008 (Gibbs et al. 2015). The Cattle Agreement prohibits major meat distributors to buy meat produced from livestock on pastures established on former forest land after 2009 (Gibbs et al. 2016). The Soy Moratorium was set to run out in 2012, but has been renewed on a yearly basis since then. In 2016 it was renewed for an indefinite period of time since all involved parties agreed that not enough mechanisms were in place to protect the Brazilian rainforests from farmers and investors. As soon as the involved parties agree that the implemented protection mechanisms are sufficient, the agreement will be obsolete (Adario 2016). The cattle agreement is scheduled to run out in 2019. This shows how uncertain the process of policy implementation is. The volatility has not been incorporated into the qualitative and quantitative scenarios, which ultimately introduces uncertainties into land-use change modeling on the basis of scenarios that consider such policies. Furthermore, political decisions in regard to the infrastructural development of the region have been incorporated into the quantitative scenarios in an insufficient manner. The BR-163 is considered to be paved from Cuiabá to Santarém which does not reflect current conditions. Especially in the northern parts of PA the road remains unpaved (Abers et al. 2016), and thus less suitable for the transport of agricultural products to export harbors and national markets. Moreover, the status of the road also puts a constraint on the agricultural development in the region as accessibility plays an important role in regard to the suitability of an area for conversion into agricultural productive land. Finally, other viable infrastructure options that might lead to new land-use patterns have not been accounted for. The expert team extensively discussed the possibility of incorporating a railroad line, financed by Chinese investors, into one of the scenarios which would have caused competition for the BR-163 and would have added another attractor for land-use change in the region. Due to resource constraints this option could not be realized.

Biophysical uncertainties were mainly introduced by not incorporating processes that would have had decisive influence on simulated land-use change and emerging land-use patterns.

Climate change is not implemented in the quantitative scenarios. It was planned to integrate climate change in form of changing crop yields, driven by changing precipitation amounts and patterns. This would have strongly impacted emerging land-use patterns as some regions might have benefitted from increasing precipitation and other regions might have to endure negative effects due to decreasing precipitation and extreme events (Altieri and Nicholls 2017). Also, cropping patterns would have been influenced as some crops would have been favored and other crops would not have been suitable for agriculture under changing climate conditions (e.g. Wood et al. 2014). On the one hand, not integrating climate change causes uncertainties in regard to future land-use change as well as cropping patterns. On the other hand, it was argued that the effects of climate change would not play a significant role within the temporal scope of the scenarios (2010-2030). Moreover, it would have been an asset to implement agricultural intensification in a more detailed manner. Currently, a biological maximum in regard to the net primary productivity on pasture cells (in respect to soil conditions or applied forage plant) is not considered. This causes uncertainties as we assume intensification of pastures to occur unimpeded. Finally, uncertainties are introduced by not considering the degradation of agricultural land in the scenarios (e.g. Hohnwald et al. 2016). Degradation was only assessed on the basis of simulated land-use from 2010-2030 but the feedback to land-use due to areas degrading to a point of non-suitability for agricultural production was not implemented.

5.2. Summary: approaches to reduce uncertainties, improve credibility as well as acceptance of scenarios

In order to improve scenarios a reduction of uncertainties is essential. A myriad of measures is imaginable to reach this goal. We will categorize these into the groups: expanding scope of scenarios, participation of stakeholders, an improved representation of socio-economic behavior, interactive scenarios, and integration of surprises. Furthermore, we raise the issue of an appropriate quality control in all scenario building steps.

a. Expanding scope

The scope of scenarios can be expanded, on the one hand, by increasing the detail of a representation of driving forces and, on the other hand, by increasing the detail of a representation of constraints. Population growth could have been quantified on a regional or even local basis in order to realistically depict population dynamics along the agricultural pioneer frontier and in other parts of both federal states instead of quantifying population growth on a state-wide basis. Population growth assumptions in the *Sustainable Development Scenario* could have been quantified in a non-linear fashion in order to reflect infrastructure development, especially along the pioneer frontier, and improved livelihood conditions. Instead of just quantifying agricultural production growth according to population growth in Asian countries, the rising per capita income in this region could also have been integrated into quantitative scenarios in order to express changing consumption behavior away from a crop-oriented diet towards meat-oriented consumption. Agricultural production increases, especially in the *Trend Scenario*, could have been realized in changing proportions of agricultural intensification and expansion of agricultural land. The pavement of the BR-163 could have been incorporated in a dynamic way in order to indicate ongoing infrastructure development. In addition to just increasing the detail of considered driving forces, more research effort and time could have been invested to integrate as yet not considered driving forces. The incorporation of the current status of land tenure rights and their implementation as well as enforcement could have been implemented into the quantitative scenarios in order to more authentically represent the situation in PA.

Also constraints to land-use change could have been given more thought and hence more detail. The expansion of agricultural land (for production of cash crops) in specific regions of PA could have been made impossible or at least less likely due to biophysical constraints as the discussed slope in this region. Here an establishment of mechanized, large-scale agriculture does not seem very realistic. Also, oversimplification of constraining factors could have been avoided. A biological maximum to agricultural intensification of pastures would have been an asset to the scenarios. The biological maximum could be defined by prevailing soil conditions or by the type of forage plant that was sown. Moreover, a dynamic expansion or contraction of conservation areas would have helped to improve the scenarios, increase acceptance and credibility. It is less realistic to assume that their current extent will stay constant within a time period of 30 years. Finally, other neglected constraints to agriculture and agricultural expansion could have been considered. So far, land degradation due to agricultural practices or soil erosion is not implemented in the scenarios. This measure would have considerably improved the scenarios.

b. Participation

Participation of stakeholders in the process of scenario construction will greatly improve scenarios due to the incorporation of different points of view. For instance, a practitioner will think in different temporal and spatial dimensions as planning authorities or policy makers. In regard to the Carbiocial Scenario process, several stakeholder workshops were held in 3 different destinations along the BR-163. Stakeholders were asked to give their opinion on a general agricultural and political development in their respective regions. Furthermore they were asked to answer specific questions that were considered important for the generation of qualitative scenarios in interview situations. In contrast, stakeholders were not consulted in the process of scenario quantification. As mentioned this process was expert-driven and the quantified and simulated scenarios were presented to stakeholders in the course of field days close to the phase of result dissemination. Hence, stakeholders could not influence the process of translation of qualitative storylines into quantitative scenarios. Especially this step of the scenario construction process would have benefitted extremely from feedback given by stakeholders and would have considerably improved the acceptance of the final scenarios. Feedback from farmers could have improved the quantification of constraints to agricultural expansion. Also, the contraction or expansion of conservation areas could have been estimated by considering strategies of planning authorities. NGOs (especially NGOs representing the native population of Brazil) could have could have commented on the integration of further indigenous conservation areas into the quantitative scenarios.

c. Improved representation of socio-economic behavior

The representation of socio-economic behavior could be enhanced considerably. Currently, the land-use change model only marginally reflects the diversity of actors along the agricultural pioneer frontier in Brazil. The subdivision of actors is currently oriented toward the land-use types that compete for land resources within the land-use change model. 3 actors are considered: crop farmers (crop area), cattle ranchers (pasture) and general population (urban area). In reality the situation is more diverse in terms of actors and their respective land-use behavior. For instance, the current setup of the land-use change model neglects the differentiation between smallholders and export oriented farmers that manage estates as large as 10,000 ha. Their respective behavior in terms of expansion of agricultural land, land management, and types of crops cultivated varies considerably (Schmink and Wood 2013).

Also the representation of migration only mirrors observed migration dynamics in a simplified manner. We quantified migration, and thus population dynamics as a linear process. More likely, in-migration might speed up in times and regions of agricultural consolidation, infrastructure development, and emerging prosperity or slow down in times of declining world market prices for cash crops or meat. Further, out-migration might speed up if work opportunities become sparse or land tenure rights continue to be only marginally implemented and enforced (Randell et al. 2014) in PA.

d. Interactive scenarios and surprises

Also the approach to build scenarios in an interactive fashion would have contributed toward the credibility of the final scenarios. Dividing the entire time horizon of the scenarios into smaller intervals and specifying the driving forces of land-use change for each single interval in respect to the calculated dynamics of the preceding interval would have led to non-linear characteristics of these driving forces (also see Alcamo et al. 2008). This measure would have also allowed for the integration of driver feedback into the scenarios. For instance, the slow-down of in-migration as assumed in the Sustainability Scenario which especially manifests in the first half of the scenario time frame (2010-2020) could have led to a decreasing rate of agricultural production, and thus agricultural land expansion in the latter interval of the scenario period (2020-2030).

As discussed before, the policy process in Brazil, especially along the pioneer frontier, is rather volatile (Campbell 2011; Campbell 2014). This could have been incorporated into the scenarios in the form of surprises. For instance, one scenario could have reflected a sudden change in conservation policy in form of a contraction of conservation areas, thus increasing the available land resources for agricultural land expansion. Also, a sudden shift in terms of infrastructure development policy could have increased the creativity of the final scenarios. If we assume a situation in which the pavement of the BR-163 is stopped at a specific point in time or at a certain location, pressure on land resources would be displaced to other regions of the study area. This measure would have resulted in distinctly different land-use patterns as calculated for the existing scenarios.

e. Quality Control

Another important aspect of scenario construction is quality control. Several authors (e.g. Alcamo et al. 2008; Alcamo and Henrichs 2008) have elaborated on the possibilities to integrate a high degree of quality assurance into scenario building. Also, Priess and Hauck (2014) have raised the issue of an appropriate incorporation of quality control bodies into the scenario construction process. Due to time and resource constraints, this feature was not well represented in the Carbiocial Scenario construction process. Final scenarios were only evaluated on a less formal basis as it would have been necessary. As mentioned before, stakeholders were not at all integrated, for instance in form of iterative feedback loops, in the process of scenario quantification. Quality control did occur at rare intervals during the process of scenario quantification. The final quantified scenarios were only quality checked by experts with predominantly little experience in the field of scenario construction. The aspect of quality control could have been better integrated by establishing a scenario panel consisting of experts as well as stakeholders. This scenario panel would have had to check the storylines as well as quantified scenarios at set time intervals throughout the whole scenario building process. This measure would have greatly increased the credibility and acceptance of the final scenarios and decreased emerging uncertainties.

6. Conclusion

Due to the spatial distribution of research sites and the multitude of CarBioCial and Carbioma interactions, the feedback loops with Brazilian partners and stakeholders at various levels of involvement lacked a certain degree of continuity and happened sometimes rather arbitrarily. One learning for future research is certainly, that a stronger investment in the outcome might have been evidenced had all co-operations and participations in the research process been negotiated and institutionalized at an early stage of the project. In our position, we genuinely tried to incorporate all available data into our storylines and received predominantly positive feedback during our feed-back-tour.

Chapter 6: Syntheses

1. Syntheses

The overall objective of this thesis was to conduct a model-based analysis of land-use change in Southern Amazonia. The analysis was based on the outcome of four scenario simulations. The simulated land-use change scenarios facilitated an investigation of the reconcilability of an increasing agricultural production in order to fulfill anthropogenic consumption demands and the minimization of negative consequences on ecosystems and biodiversity. Further it was necessary to critically review the scenario quantification process in order to increase consistency and acceptability of the scenarios. This chapter, complementary to the discussions presented in chapter 2 through 5, summarizes research findings in the context of three research objectives. Moreover, advantages and limitations of this thesis are discussed and an outlook is presented that comprises further research needs as well as possible future applications of the results in this thesis.

1.1. Summary of findings

The first research objective was to explore sensitivities of land-use change modeling- and subsequent impact assessment results to (1) different initial land cover products, (2) input variables derived from the most commonly utilized databases (in respect to the study region) and (3) the variety of model parameter values resulting from different methods used for model parameter estimation. Furthermore, a possible range of modeling results that can be attributed to the sensitivities was to be identified.

This research objective was addressed in the following way:

- <u>The land-use change modeling framework LandSHIFT was adapted to the study area.</u>

The Moderate Resolution Imaging Spectroradiometer (MODIS) land-cover dataset (MCD12Q1) for the year 2001 (Friedl et al., 2010) and the Global Land Cover (GLC2000) dataset for the year 2000 (Bartholomé & Belward, 2005) were employed for model initialization and base map generation. Moreover, the model input comprises spatial datasets in regard to human population density, terrain slope, river- and road network as well as protected areas. Crop yields and biomass productivity of pasture were calculated with the Lund-Potsdam-Jena managed Land (LPJmL) model (Bondeau et al. 2007) on a 0.5° raster for current climate conditions. All of the above datasets describe the biophysical and socio-economic conditions of the study area and were converted to the 900x900m raster the land-use change model now operated on. Furthermore, data used to drive the magnitude of LULCC were taken from two commonly utilized databases for agricultural statistics. On the regional scale, data concerning crop production and cropland area was taken from the municipal livestock and agricultural production survey available at the IBGE database (IBGE 2015). On the country scale data regarding crop production and cropland area was taken from the FAOSTAT database (FAO 2013) and was downscaled to be available as model input.

- Land-use change modeling sensitivities and the resulting range of LULCC modeling results were assessed.

LULCC was simulated based on two different land-cover datasets, two different statistical databases, and the estimation of parameter weights utilizing two different methods, totaling eight different model setup combinations.

The main difference between both employed land cover products was the amount of modeled LULCC. While simulating LULCC based on the MODIS land cover dataset, modeled LULCC was 7% to 23% higher than in the cases where the GLC2000 land cover product was employed to initialize the model. Furthermore, the choice of initial land-cover product also influenced the location of LULCC, thus also affecting the amount of modeled deforestation.

The only specific modeling result that showed a sensitivity to agricultural statistics data was the conversion of agricultural productive land into fallow land. In the case of employing FAO derived statistics, there was almost no need to convert agricultural land into fallow land due to an overachievement of agricultural production. The contrary applied to the cases where the model was driven with IBGE derived statistics. Here an area varying between 2,815 km^2 to 9,689 km^2 was converted into fallow land.

The highest sensitivity of modeling results was discernible in respect to the method used to estimate parameter weights. The amount of modeled LULCC differed by 20% to 34%. Parameter weights also affected the type of natural vegetation that was converted into cropland or pastures in respect to the applied land-cover product.

- The land-use change model was evaluated for each model setup combination.

Two methods to evaluate model performance in terms of quantity and location of modeled LULCC were employed. Both methods compare modeled and observed cropland area on the municipal level (model efficiency) and grid level (Fuzzy Kappa coefficient).

The highest overall model efficiency was achieved by employing the MODIS land cover dataset with input variables derived from the IBGE or FAO database and parameter weights estimated with a method based on the AHP method (Saaty 1990) (further referred to as AHP method). The highest overall Fuzzy Kappa values were realized when using the MODIS land cover product in combination with FAO or IBGE input data and the AHP method to estimate factor weights.

These findings indicate the best combination of land cover dataset, agricultural model input, and method to estimate parameter weights in order to capture past land-use development in the study area. Hence, the MODIS land cover dataset, input variables derived from the IBGE database and the AHP method to estimate parameter weights were employed to simulate land-use change scenarios in subsequent steps of this thesis.

- <u>Uncertainties concerning subsequent impact assessment results were investigated.</u>

Modeled land-use maps for each model setup combination were used as input for the model-based simulation of GHG-emissions as a consequence of LULCC.

Annual CO_2e-emission estimates for PA for the period from 2000 and 2010 varied by 24%. In MT, the variance was even higher. Here, annual CO_2e-emission estimates for the same period varied by 40%. The emission estimates were strongly influenced by the choice of initial land-cover dataset as well as the applied method to estimate parameter weights.

The second research objective was to investigate land-use changes, in terms of location and extent, which can be expected by assuming four different development pathways for Southern Amazonia. Moreover, environmental consequences of the simulated land-use changes in terms of GHG-emissions and the effect of a conversion of natural habitats on the distribution ranges of vertebrate species were to be assessed.

This research objective was realized in the following way:

- <u>Land-use changes based on 4 different development pathways were simulated and assessed.</u>

Four socio-economic scenarios for Southern Amazonia were constructed within the framework CarBioCial project. They comprise storylines and numerical model input and were used to simulate LULCC with the adapted and enhanced LandSHIFT model.

The largest reduction of natural vegetation cover was simulated for the *Trend Scenario*. The main driver was the expansion of pasture. The loss of natural vegetation could be considerably reduced in the *Legal Intensification Scenario*.

The largest expansion of pasture area was simulated for the Trend Scenario. The highest increase of cropland area is projected for the *Sustainable Development Scenario*.

It was found that an increase of pasture productivity leads to a reduction of pasture area by close to 44% when comparing *Trend* and *Legal Intensification Scenario.*

- <u>N_2O- and CH_4-fluxes from agricultural soils were calculated.</u>

N_2O-and CH_4-emissions from agricultural soils based on average N_2O-and CH_4-emissions for different land-use types in Brazil were calculated for each modeled land-use scenario.

N_2O-emissions increase most for the *Trend Scenario*, mainly due to an expansion of pasture area. Whereas, a decrease of N_2O-emissions from agricultural soils was calculated for the *Sustainability Scenario* despite the strong expansion of cropland area.

The same can be said about CH_4-emissions. The highest increase was calculated for the *Trend Scenario* due to a strong expansion of pasture area. For all other scenarios, CH_4-emissions decreased considerably due to a reduced expansion of pastures in comparison to the *Trend Scenario* and an expansion of cropland area. Cropland soils, especially young cropland (≤10 years), were identified to function as a sink of CH_4.

- <u>CO_2-fluxes from agricultural soils from agricultural soils were calculated.</u>

CO_2-fluxes derived from results of field experiments in the study area that investigated soil organic carbon stocks were calculated for each modeled land-use scenario.

An increase of CO_2-emissions was estimated for all scenarios. This was mainly attributable to emissions from cropland. The emission increase due to a decline of young cropland (≤10 years) in favor of old cropland (>10 years) could not be compensated by the decline of CO_2-emissions from pastures that was calculated for all scenarios except the *Trend Scenario* in MT and for the *Sustainability Scenario* in PA. Young cropland acted as a sink of CO_2-emissions while old cropland acted as a CO_2-source.

- <u>The effect of a conversion of natural habitats on the distribution ranges of vertebrate species was assessed.</u>

It was possible to spatially link modeled LULCC (specifically the conversion of natural habitats) and information regarding the occurrence of vertebrate species for each calculated land-use scenario. Additionally, the indicator Biodiversity Intactness Index was calculated.

As the investigation of modeled LULCC showed, a reduction of the conversion of natural habitats could be considerably reduced for all scenarios in comparison to the *Trend Scenario* (Chapter 3). Of the remaining converted natural habitat area, only 11-15% (in respect to the assessed taxon of vertebrate species) were known habitats of vertebrate species in the case of the *Sustainability Scenario* in PA. In MT, the strongest reduction of converted natural habitats was simulated for the *Legal Intensification Scenario* (-86%) with the caveat that 100% of the remaining converted natural habitat area were habitats of the assessed vertebrate species taxa.

The effects of a loss of natural habitats on vertebrate species diversity were confirmed by the assessment of the BII. Decreasing BII values in the case of all simulated scenarios for all assessed taxa and categories were calculated with few exceptions in PA and MT.

The third research objective was to critically review analyze the process of translating stakeholder-generated storylines into suitable model inputs that can be used to generate quantitative scenarios.

This research objective was accomplished in the following way:

- <u>The process of translating storylines into suitable model input that was applied in the Carbiocial project was described and critically reviewed.</u>

Storylines were developed by a team of experts who were asked to imagine possible socio-economic development trajectories for Southern Amazonia. The storylines describe different future development pathways (explorative scenarios) in the form of narratives. A crucial step in the development of combined qualitative and quantitative scenarios was to translate the stakeholder generated scenarios into numerical model input while maintaining consistency.

Based on the storylines for each scenario a set of land-use drivers was identified to quantitatively describe the evolution of key factors until 2030. The key factors were chosen based on an analysis of deforestation drivers in literature (Lambin and Geist 2003) but were already oriented toward the data input requirements of the applied land-use change models. They included quantitative information on population development, crop production, livestock numbers and crop yield increases due to technological change, as well as assumptions regarding land-use policy, infrastructural development, protected areas, and the degree of law enforcement.

Statements from each storyline regarding these topics were extracted and interpreted in light of their potential meaning for the land-use change modeling process. This qualitative information was translated either into numerical data describing socio-economic trends or into rules that were integrated into the land-use change models. Some storyline assumptions could not be translated into model input while some model input could not be deduced from storyline assumptions. This causes inconsistency between the storylines and the quantitative model input.

Consistency could mostly be maintained as most relevant storyline assumptions could be directly translated into numerical model input. The only exceptions hereof are the urbanization trend in Southern Amazonia until 2030 and the possible dynamics (changes in regard to extent and location) of conservation areas in the study area.

- The effectiveness of this process was analyzed.

To analyze the effectiveness of the applied process uncertainties that arose are identified.

Uncertainties could be categorized according to the system they relate to. Hence, following categories were used: social-, economic-, political-, and biophysical uncertainties. The identified uncertainties resulted from simplifications, and thus a reduced level of detail in regard to the representation of driving forces (e.g. linear development of population growth) as well as constraints (e.g. missing integration of land degradation) of LULCC. Moreover, a reduced integration and participation of stakeholders led to uncertainties. For instance, stakeholder participated in the process of developing storylines but were not part of feedback loops throughout the process of the quantification of the storylines. Finally, the simplified representation of socio-economic behavior in the quantified scenarios led to uncertainties in respect to the modeled land-use scenario results. For example, migration as a driver of land-use change, especially along an agricultural pioneer frontier (e.g. Verburg et al. 2014), could have been quantified in a non-linear way in order to reflect the dynamic nature of migration processes (e.g. Caviglia-Harris et al. 2012).

1.2. Advantages and Limitations

As Chapter 2 showed, modeling land-use change always involves a certain degree of uncertainty that can result in a range of modeling results (e.g. Tayyebi et al. 2014; Gollnow et al. 2017). This uncertainty can be related to two main sources. One is the input data that is used to run the model. The other is the model structure itself. One advantage of this thesis is the investigation of sensitivities of the modeling results to different input data sources, land-cover products and methods to estimate parameter weights. Olofsson et al. (2012) and Schmitz et al. (2014) emphasized the importance to integrate this sensitivity perspective into any land-use change modeling exercise. Moreover, the presented research goes beyond the one at a time approach to analyzing model sensitivity (Czitrom 1999) and analyzes not only input data but also the effect of model processes on sensitivity.

One part of this thesis was to evaluate possible combinations of land-cover dataset, input data source, and method used to estimate parameter weights utilizable to model land-use change in respect to the study area and the resolution of the land-use change model. This poses another advantage. Usually, model evaluation is based on a distinct set of model outcomes, meaning that model input and methods are chosen prior to model evaluation (e.g. Mas et al. 2014). In this thesis, the choice of input data source, land-cover dataset as well as method used to estimate parameter weights was made on the basis of the evaluation of possible combinations of the mentioned inputs and methods.

GHG-emission estimates discussed in this thesis (see Chapter 3) are based on a very broad data basis. The calculation of N_2O- and CH_4-emissions was based on an extensive literature review (Meurer et al. 2016) while estimates of CO_2-emissions are based on soil organic carbon stock changes which have been observed in the course of field experiments in the study area (Strey et al. 2016). This broad data basis, and especially the direct observation in the field, poses an advantage to other studies of GHG-emissions in the study area. For instance, Galford et al.´s (2010) as well as Aguiar et al.´s (2016) study of GHG-emissions in Mato Grosso and the Brazilian Amazon respectively were based on literature alone. Also in contrast to the study of Galford et al. (2010) (who divided pastures into young (0 – 3 years), middle (4 – 5 years), and old (≥ 6 years)), this thesis additionally focused on age-related CO_2-emissions from pastures and croplands, thus allowing for a more detailed exploration of possible GHG-emission futures.

Chapter 4 of this thesis is among the first to integrate an investigation of the impact of projected LULCC on a proxy for overall terrestrial vertebrate diversity on a regional scale which constitutes an advantage in the field of environmental impact assessment. A multitude of studies explore the impacts of land-use changes on biodiversity in the tropics (e.g. Heckenberger et al., 2007, Gentili et al., 2014, Laurance et al., 2014, Chaplin-Kramer et al., 2015, Solar et al., 2016; Newbold et al., 2016). However, these studies focus on biodiversity in general (Heckenberger et al., 2007; Laurance et al., 2014; Chaplin-Kramer et al., 2015), on a single specific species as an indicator for biodiversity (Gentili et al., 2014; Solar et al., 2016) or on a global perspective (Newbold et al., 2016). Thereby, they cannot explicitly assess threats to the regions` overall vertebrate diversity.

As described in detail in Chapter 5, one central advantage of this thesis is the exploration of land-use futures based on combined qualitative and quantitative scenarios. The approach applied for this purpose is called the Story and Simulation approach (SAS) (Alcamo et al. 2008). This approach has the advantages of helping to produce scenarios that are relevant to experts as well as stakeholders, producing legitimate scenarios due to the active involvement of all relevant interest groups and the possibility to easily communicate resulting knowledge to these groups. The scenarios include numerical data generated by computer models which are transparent and reproducible. Moreover, the applied process led to creative assumptions regarding possible socio-economic futures as different mindsets (e.g. practitioners and planners) are integrated (e.g. Raskin et al. 2005; Folhes et al. 2015)

The sensitivity of land-use change modeling results propagates the uncertainty of any subsequent steps of land-use modeling (e.g. environmental impact analysis) (Goldewijk and Verburg 2013; Warner et al. 2014). This could also be confirmed in Chapter 2. By modeling GHG-emissions on the basis of modeled land-use it was shown that the range of land-use change modeling results is not only propagated to the modeling of resulting GHG-emissions, it is even slightly increased. This is a limitation of this thesis as all environmental impact assessments that are part of the thesis (Chapters 3 and 4) are based on land-use change modeling results. Moreover, all of the methods utilized to assess the environmental impacts incorporate their own sensitivities and uncertainties as discussed in the respective chapters.

Another limitations of this study was the quality of input data as well as simplifications of modeled environmental processes as discussed in Chapter 3 and 5. These limitations led to uncertainties in regard to the modeling results. One such limitation due to input data quality was discussed in Chapter 3. IBGE-derived data underestimates crop production as a result of illegal agricultural activity in Brazil as was suggested by Lawson et al. (2014). Whereas MODIS satellite images capture all cropland in respect to the employed method of identification and classification. This led to a mismatch of crop production and production area of 35%. Consequently, deforestation might be also underestimated as in the land-use change model increasing crop production is first realized on fallow cropland. Furthermore, simplification of modeled environmental processes or not-integration of agricultural management practices relevant in the study area causes uncertainties in regard to the final modeling results. As was found by Lapola et al. (2014), double cropping has been adapted by more than 60% of the farmers in Mato Grosso. This means that more agricultural production can be realized on less cropland area. This management option is not integrated in the applied land-use change model which could have caused an overestimation of a loss of natural vegetation as a result of LULCC. Moreover, all scenarios in this thesis assume that increases of crop yields are achieved by technological progress or an intensification of agricultural management. Changing climate conditions (temperature, precipitation) are not considered. Whereas Arnell et al. (2016) expect changes in temperature and precipitation to become more intense in the future, possibly with stronger negative impacts in crop yields (IPCC 2014).

As discussed extensively in Chapter 5, the translation of storylines into quantitative data (numerical model input) that can be used to model land-use change scenarios involved limitations. They related to the methods employed in the translation process or to simplification of assumptions in accordance with the simplification of modeled processes. An example for limitations in regard to the methods employed in the translation process is the quantification of dynamic processes in a linear way (e.g. population growth). Not taking into consideration that there is a biological maximum to the net primary productivity of pasture cells under certain conditions (soil conditions, type of forage plant) is a limitation that relates to the structure of the applied land-use change model.

1.3. Outlook

When a highly dynamic land-use system meets an uncertain future, simulation models in combination with the scenario technique provide a framework for identifying potential environmental consequences associated with specific development trajectories (Duinker and Greig 2007). Especially in a region that experiences agricultural expansion and intensification as well as associated processing industries as the most important means of economic development such as Southern Amazonia (Soler et al. 2014), the potential for negatively influencing the environment is high (Nobre et al. 2016). Hence, there is an urgent need for assessing environmental risks and investigating alternative strategies that help to reconcile increasing food production and conservation of natural capital (Arvor et al. 2017).

The following approaches to improve scenario-based land-use change modeling on a regional scale could be and were deducted from the preceding chapters of this thesis. Need for research exists in regard to the further refinement of the LandSHIFT model in order to capture specific processes that have a strong effect on modeled land-use on the regional scale. Currently land-use is subdivided into three sectors: cropland, pastures, and urban land. This subdivision does not take into account a further subdivision that is witnessed in regard to the development of agricultural pioneer frontier in Southern Amazonia (e.g. Pacheco 2012). Agricultural land-use in MT and PA can be separated into smallholder agriculture and large-scale, mechanized agriculture. Both manage land adapted to the region they operate in (with its biophysical characteristics and its land tenure situation), the financial means they can resort to, and their economic situation in general (de Andrade Vasconcelos et al. 2017). The measure of integrating both forms of land management would allow for a more detailed investigation of land-use dynamics within the region as well as more precise and differentiated recommendations in regard to the reconcilability of future agricultural-, and thus economic, development and a reduction of negative environmental consequences. Moreover, an integration of specific land management strategies (e.g. double cropping) that are largely adopted in the study area would greatly enhance the investigation of possible development trajectories. For instance, the agricultural management method of double cropping that is employed by smallholders as well as large-scale land-users in MT and PA (e.g. Lapola et al. 2014; Dias et al. 2016) is not integrated in the applied land-use change model. The incorporation of said mechanism into the land-use change modeling framework would result in a more realistic picture of the pressure on natural resources in the region.

The findings of this thesis can be applied to future research interests. Agricultural pioneer frontier regions exist on different continents (e.g. Temudo 2014; Diepart et al. 2016; Van Hecken et al. 2017). The adapted and enhanced land-use change model can be reapplied to different tropical and subtropical areas that experience agricultural pioneer frontier dynamics, especially if further enhancements that have been discussed in the above paragraph could be realized. Another important application of the findings presented in this thesis would be a more comprehensive investigation of environmental consequences in the study area. For instance, the consequences of further agricultural intensification on available freshwater resources could be explored by coupling land-use change modeling results and a model of water quality. Furthermore, the findings in regard to the process of translating storylines into quantitative model input can be applied to improve future quantification attempts. For instance, different methods (e.g. Jetter and Kok 2014; Kok et al. 2015) of translating narrative assumptions into numerical information could be applied to formalize this process further. An increased integration of stakeholders and different experts in the process of storyline translation could be realized in order to minimize uncertainty due to considering that the interpretation of a narrative scenario assumption might differ intra- and interdisciplinary (van Dijk et al. 2016).

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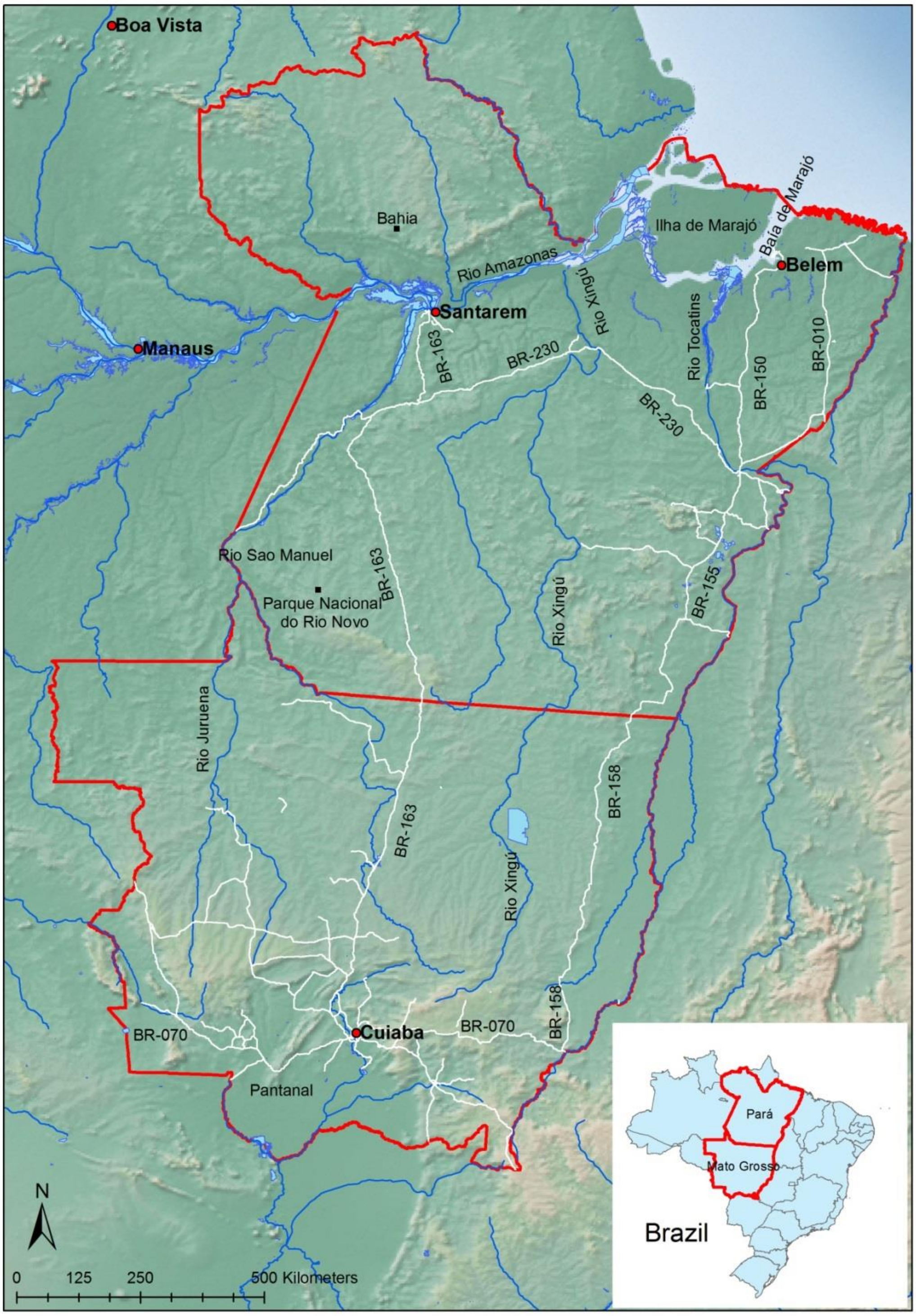
Appendix A

Supporting Information for Chapter 3

1. Map of the study region

Figure A-1: overview map of the study region (Mato Grosso and Pará in Brazil). Based on ESRI data regarding river network, cities and state borders. Road Network extracted from Google Maps.



2. Tables

Table A-1: LandSHIFT land-use types and their aggregation used for mapping.

LandSHIFT land-use types	aggregated land-use types
Evergreen needle forest, evergreen broad-leafed forest, mixed forest	Forest vegetation types (Rainforest)
Closed shrub land, open shrub land	Shrubland vegetation types
Woody savannah, savannah	Savannah vegetation types (Cerrado)
Fruits, maize, groundnut, beans, rice, cassava, soybean, sugarcane	Cropland
Rangeland, pasture	Pasture
Barren land	Barren land
Grassland	Grassland
Wetlands	Wetland
Urban	Urban Area
Fallow land	Fallow land
Water	Water

Table A-2: Population development in Pará and Mato Grosso. Population numbers in 2010 and change rates until 2030.

State	2010	Change 2010 – 2030 [%]		
	Population	*Trend*	*Legal/Illegal Intensification*	*Sustainable Development*
Pará	6,913,180	+35	+35	+32
Mato Grosso	2,795,890	+35	+35	+29

Table A-3: Livestock Units in Pará and Mato Grosso. Livestock Units in 2010 and change rates until 2030.

State	2010	Change 2010 – 2030 [%]		
	Livestock Units	*Trend*	*Legal/Illegal Intensification*	*Sustainable Development*
Pará	8,121,010	+103	+146	-70
Mato Grosso	16,970,600	+49	+80	-70

Table A-4: Crop yields and crop production in Pará and Mato Grosso. Crop yields and crop production in 2010 and change rates until 2030.

	Crop type	Crop yield				Crop production			
		[t/ha]	Change 2010 – 2030 [%]			[kt]	Change 2010 – 2030 [%][2]		
		2010	*Trend*	*Legal/Illegal Intensification*	*Sustainable development*	2010	*Trend*	*Legal/Illegal Intensification*	*Sustainable development*
Pará	Fruits	16.05	+42.35	+42.35	+85.06	740.67	+123.52	+123.52	+273.58
	Maize	3.81	+70.32	+70.32	+121.42	519.25	+89.36	+129.13	+55.59
	Groundnut	2.1	+40.37	+40.37	+82.48	0.19	+109.73	+109.73	+57.93
	Beans	0.76	+49.41	+49.41	+94.23	36.49	+146.83	+146.83	+1978.76
	Rice	2.64	+61.56	+61.56	+110.03	263.87	+145.35	+145.35	+125.74
	Cassava	16.49	+45.92	+45.92	+89.70	4596	+67.11	+67.11	+88.82
	Soybean	2.86	+39.16	+39.16	+80.91	243.61	+177.75	+236.07	+2447.96
	Sugarcane	81.31	+51.40	+51.40	+96.82	668.74	+8.12	+8.12	+8.12
Mato Grosso	Fruits	16.05	+42.35	+42.35	+85.06	57.77	+226.64	+226.64	+542.83
	Maize	3.81	+70.32	+70.32	+121.42	8164	-0.53	+20.36	+69.15
	Groundnut	2.1	+40.37	+40.37	+82.48	4.52	-13.19	-13.19	+55.02
	Beans	0.76	+49.41	+49.41	+94.23	133.81	-24.39	-24.39	+701.28
	Rice	2.64	+61.56	+61.56	+110.03	686.3	+97.44	+97.44	+125.74
	Cassava	16.49	+45.92	+45.92	+89.70	496	+8.79	+8.79	+103.03
	Soybean	2.86	+39.16	+39.16	+80.91	4921	+42.05	+71.88	+119.70
	Sugarcane	81.31	+51.40	+51.40	+96.82	9390	+71.88	+71.88	+71.88

[2] high change rates (beans, soy) due to substitution of dietary meat intake and relatively low production values in 2010

1. Method for measuring and calculating SOC changes

To analyze the SOC stocks changes after land-use conversion 29 plots of a size of 100 m x 100 m were identified along a research transect that comprised plots near Novo Progresso, Sinop and Cuiaba (Strey et al. 2016).

The plots included three different land-use types: native vegetation, pastures and crop-fields. To include the most common soil types of the Amazon region (Quesada 2011) land-use types were sampled on Ferralsols and Acrisols. Soils were classified according to IUSS Working Group WRB (2014). To describe the heterogeneity of SOC within soil the plots were sampled using a grid system with a mesh size of 25 m and took 9 or 5 individual soil cores down to 100 cm on each plot. Each core was separated into sample increments of 0-10 cm, 10-30 cm, 30-60 cm, and 60-100 cm, totally we analyzed 996 samples. The samples were immediately air dried followed by an additional drying in the laboratory at 50°C until weight constancy. All samples were sieved <2 mm for further analysis. SOC concentrations were measured on an elemental analyzer (ISOTOPE CUBE, Elementar GmbH, Hanau, Germany) on samples previously ground with a ball mill (Retsch MM200, Haan, Germany). For calculating SOC stock the bulk density was analyzed on every plot. Therefore, a soil pit was opened (1m x 1m x 1.1m) for taking undisturbed core samples (100 cm^3) in increments of 10 cm in 3 replicates. Bulk density was calculated gravimetrically after drying the 100 cm^3 samples for 48 h by 105°C.

LULCC in most cases is accompanied by changes in the soil bulk density (Roscoe & Buurman 2003). As we assumed similar initial conditions (space for time substitution) of the plots under agriculture and their reference plots under native vegetation; the SOC stocks were mass corrected. For this the soil mass after LULCC were adjusted to the corresponding soil mass on the reference plots under native vegetation (Ellert & Bettany 1995; Poeplau et al. 2013):

$$SOCSTOCK_{corr} = SOCSTOCK_i \left(\frac{SM_i + SM_{lightest}}{CV_i} * C_{deepest} \right) \qquad \text{(A-1)}$$

where $SOCSTOCK_{corr}$ is the corrected SOC stock in MgSOC ha^{-1}, $SOCSTOCK_i$ defines the original calculated SOC stock in Mg SOC ha^{-1}, SM_i is the soil mass of the individual sample in g, and $SM_{nativet}$ the soil mass of the corresponding native vegetation in g, whereas Cv_i defines the volume in cm-3, and $C_{deepest}$ is the C concentration in % of the deepest considered soil layer. After mass correction SOC stock changes were calculated for every individual sampling point (see Table 3-1).

3. Impact of climate change and technological change on crop yields

The potential impact of changing temperature and precipitation in combination with CO_2 effect on crop growth is strongly debated in scientific literature, especially for the Amazon region (Lapola et al. 2011; Justino et al. 2013). In order to account for potential climatic effects in 2030 for agricultural development, and to augment we have conducted simulation runs for soybean and maize (for which tropical cultivar calibrations are available), using the Model of Nitrogen and Carbon dynamics in Agro-ecosystems (MONICA), that was developed for the assessment of climate change impact on agricultural production (Nendel et al. 2011). Climate data was taken from the SRES A1B scenario simulated with the IPCC Climate Model ensembles and downscaled with the Statistical Regional Model (STAR). The STAR model predicts a temperature increase of 1.7 K and a precipitation decline of 20–30%, which turns out to be more severe in Mato Grosso than in Pará. For more detailed information on climate model input see Böhner et al. (2013).

Future crop productivity will not only suffer alteration from changing climate conditions, but it may also profit from genetic improvement and progress in crop management. Therefore, we developed a new approach of how to forecast technology driven yield increases. This approach is based on the assumption that there is a biological maximum to crop yields that supersedes all environmental limitations. This limit is 35 t/ha for maize and 12.5t/ha for soybean (Specht et al. 1999). Currently, highest maize yields observed on experimental sites of the Brazilian Agricultural Research Corporation (Embrapa) in the Centro-Oeste region of Brazil are about 12.2 t/ha, while soybean yields in famer competitions reached 7.6 t/ha (Embrapa 2014, CESB 2015). We further assumed that yield increases due to technological progress can best be described by a sigmoid curve, with initial low increases that accelerate over time and slow down as they move towards the biological yield maximum. We then estimated individual sigmoid functions for each grid cell and applied them to the previously simulated yield maps of the MONICA model.

The simulation results from the MONICA model for Pará show a 21% decrease of average soybean yields from 2.4 t/ha in 2000–2005 under current climate to 1.9 t/ha in 2025–2030 under the A1B climate scenario. Second-season maize yields (braz.: safrinha), in contrast, are likely to benefit from changing climatic conditions and will experience an increase of 31% from 3.2 t/ha to 4.2 t/ha in the same time period, according to the model. This is because second-season maize is sown in the colder dry season, where relatively low temperatures inhibit biomass accumulation. A moderate temperature increase of 0.5–1.0 K as predicted for Pará, will therefore lead to an increase of second-season maize yields.

In Mato Grosso, soybean yields will decline by 17% from 2.3 t/ha in 2000–2005 to 1.9 t/ha in 2025–2030. This productivity decrease is due to a precipitation reduction of about 30% and a temperature increase of 1.0–1.7 K which accelerates the crop development and increases the probability for heat stress on crops in the already warm rainy season. Other than in Pará, maize yields in Mato Grosso are likely to stay unchanged at 5.2–5.4 t/ha. Here, the yield increasing effect of higher temperatures in the dry season is outweighed by a strong precipitation reduction, which negatively affects the mostly rain-fed maize production.

Our analysis also shows that technological progress is likely to increase average soybean yields in Pará and Mato Grosso by 76% and 69%, respectively, from 2000–2005 to 2025–2030. Maize yield increases due to genetic gains and improved crop management will turn out even clearer: Simulation results indicate productivity gains in maize production of 111% in Pará and 120% in Mato Grosso. Accounting for both effects together (climate change and technological progress), soybean yields will increase by 55% and 52%, while maize productivity will increase by 142% and 123% in Pará and Mato Grosso, respectively.

In comparison, in the scenarios the soybean yields are projected to increase by 39.2% except for the *Sustainable Development scenario* where we assume an increase by 80.9% due to the strong focus on crop production and relevant technological improvements. The maize yield is projected to increase by 70.3% in the case of the *Trend scenario* as well as both intensification scenarios. Under *Sustainable Development* we assume a maize yield increase of 121.4% due to the same reasons as stated earlier.

Appendix B

Supporting Information for Chapter 4

Figure B-1: overview map of the study region (Mato Grosso and Pará)

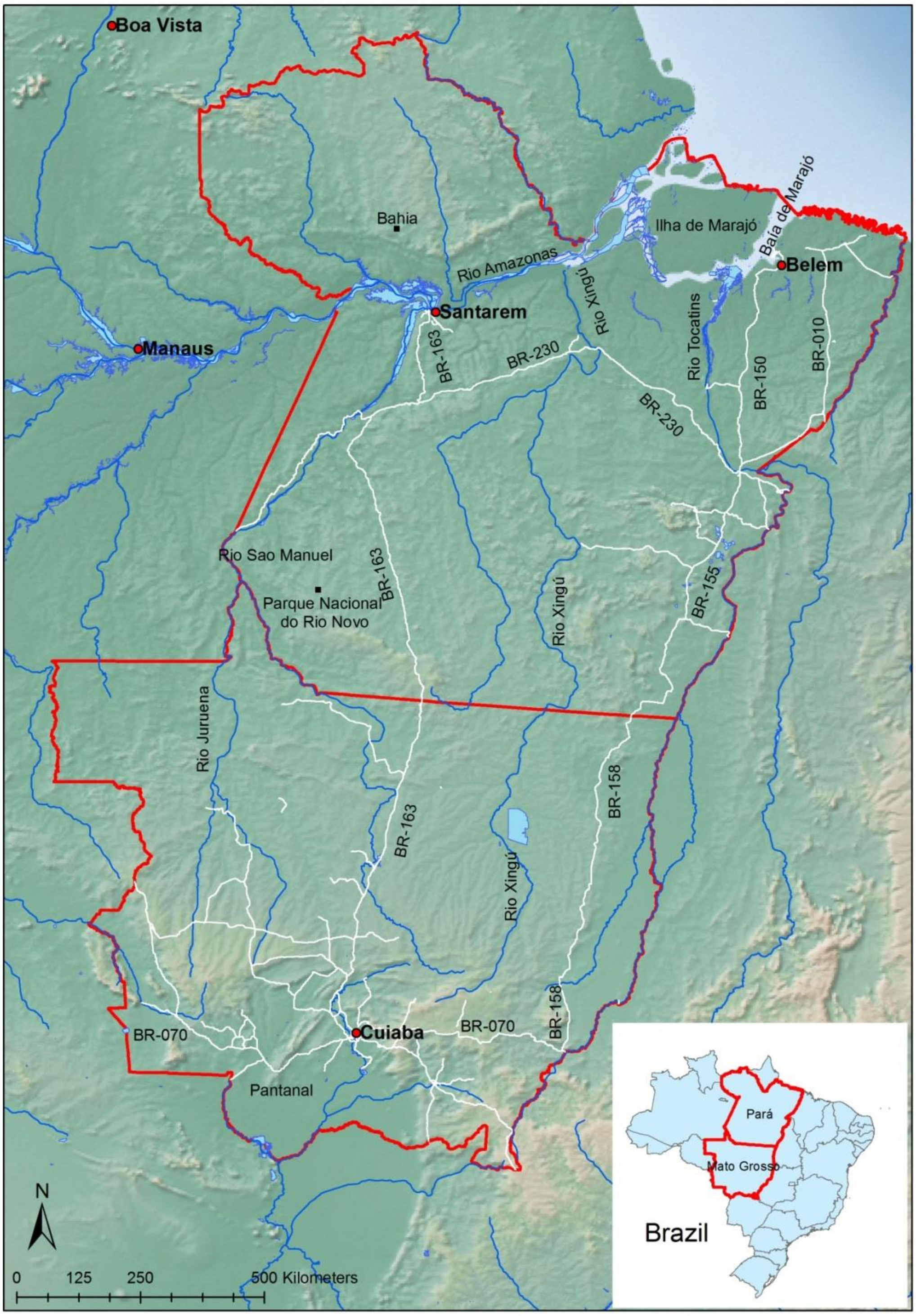


Table B-1: agricultural development in the study region between 2010 and 2030

	Crop type	Crop yield				Crop production			
		[t/ha]	Change 2010 – 2030 [%]			[kt]	Change 2010 – 2030 [%][3]		
		2010	Trend	Legal/Illegal Intensification	Sustainable development	2010	Trend	Legal/Illegal Intensification	Sustainable development
Pará	**Fruits**	16.05	+42.35	+42.35	+85.06	740.67	+123.52	+123.52	+273.58
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Table B-2: Population development in Pará and Mato Grosso. Population numbers in 2010 and change rates until 2030.

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[3] high change rates (beans, soy) due to substitution of dietary meat intake and relatively low production values in 2010